COLLABORATIVE TECHNOLOGY ALLIANCE

2001–2006 REPORT

CTA

TECHNOLOGY FOR THE SOLDIER

ADVANCED DECISION ARCHITECTURES

ADVANCED SENSORS

COMMUNICATIONS AND NETWORKS

POWER AND ENERGY

ROBOTICS

ARL

CTA

TECHNOLOGY FOR THE SOLDIER

“From the cooperative program formulation through the collaborative research efforts, the CTA program is efficiently focusing the expertise of industry, academia and the U.S. Army Research Laboratory on enabling technologies and new military capabilities needed for Army Transformation.”

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CTA

TECHNOLOGY FOR THE SOLDIER

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INTRODUCTION

In 2001, Cooperative Agreements were awarded by the U.S. Army Research Laboratory (ARL) to five consortia under the Army's Collaborative Technology Alliances (CTA) program in the following technical areas: Advanced Decision Architectures, Advanced Sensors, Communications and Networks, Power and Energy, and Robotics. The CTAs established innovative partnerships among research communities in the Army Laboratories and Research, Development & Engineering Centers (RDECs), private industry, and academia.

ARL is one of nine Science & Technology performing organizations under the Army's Research, Development and Engineering Command (RDECOM). The mission of ARL is to provide innovative science, technology and analysis, to enable full spectrum Army operations.

Each CTA combines distinctly different approaches to research resulting from collaboration among researchers in academia, industry, and Army and government labs. Academia is known for its cutting-edge innovation; industrial partners are able to leverage existing research results for transition and deal with technology bottlenecks; and the Army and other government researchers keep the program oriented toward solving complex Army technology problems.

Multidisciplinary research teams are generating the complex technology needed to solve the Army's complex problems. This approach enables the CTA program to bring together world class research and development talent and focus it on Army-specific technology objectives for application to Army Transformation.

CTA MISSION

The CTA's mission is to foster collaboration among Government-Industry-University researchers to achieve affordable transition of innovative technologies and includes these objectives:

- Identify unique Army problems that the commercial sector is not solving and focus research on technologies to solve these problems.
- Jointly plan and execute collaborative basic research with our private sector partners in conjunction with Army RDECs, other services, and non-Department of Defense laboratories.

TECHNOLOGY FOR THE SOLDIER

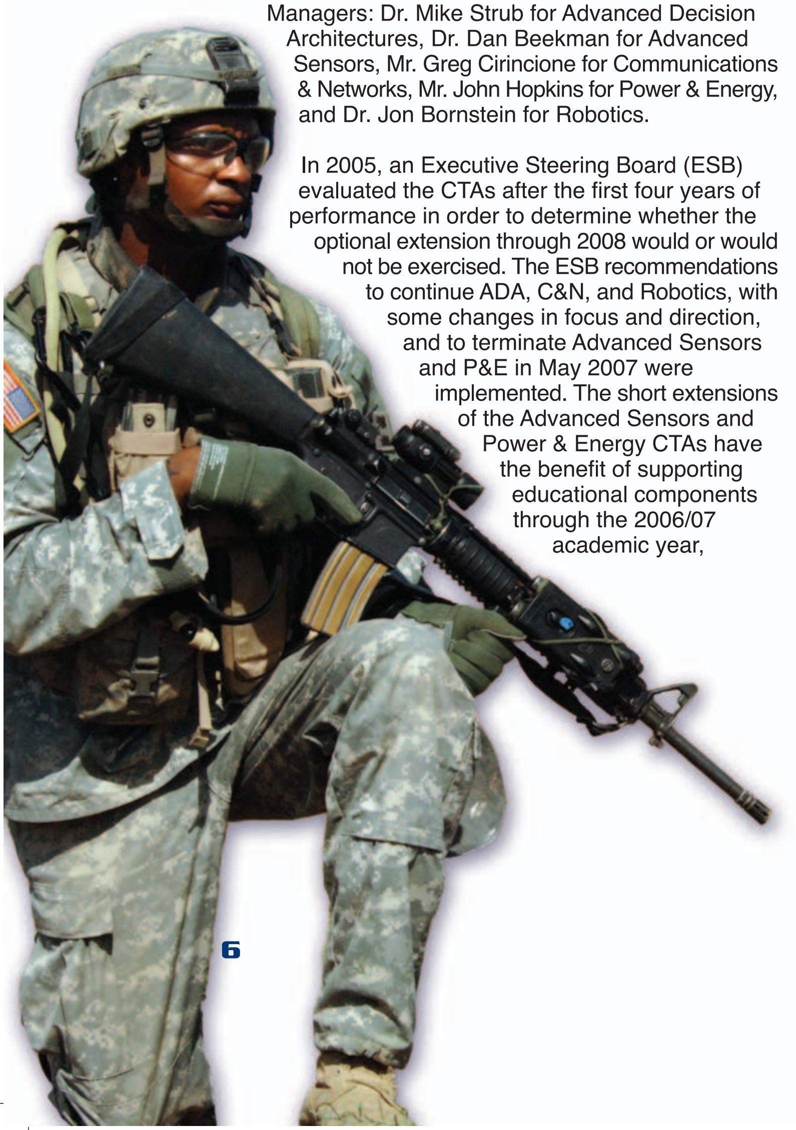
CTA OVERVIEW

- Leverage fast-moving commercial sector technology deployment.
- Transition state-of-the-art technology from the commercial world to the military tech base.

ALLIANCE MANAGEMENT

Each CTA is managed by a Lead Industrial Organization (LIO) with demonstrated expertise in specific technical areas. The LIOs are Alion/Micro Analysis & Design (Advanced Decision Architectures), BAE Systems (Advanced Sensors), Telcordia Technologies (Communications and Networks), Honeywell (Power & Energy), and General Dynamics Robotic Systems (Robotics). Over 25 universities, including many of the nation's premier research institutions, and two dozen companies located in 19 states and Puerto Rico are partners in the CTA consortia.

The government managers, who are ARL employees, include Dr. Jay Gowens, the Research Alliance Coordinator, and for each CTA, Collaborative Alliance Managers: Dr. Mike Strub for Advanced Decision Architectures, Dr. Dan Beekman for Advanced Sensors, Mr. Greg Cirincione for Communications & Networks, Mr. John Hopkins for Power & Energy, and Dr. Jon Bornstein for Robotics.



In 2005, an Executive Steering Board (ESB) evaluated the CTAs after the first four years of performance in order to determine whether the optional extension through 2008 would or would not be exercised. The ESB recommendations to continue ADA, C&N, and Robotics, with some changes in focus and direction, and to terminate Advanced Sensors and P&E in May 2007 were implemented. The short extensions of the Advanced Sensors and Power & Energy CTAs have the benefit of supporting educational components through the 2006/07 academic year, enabling a smooth transition for graduate students in the program.

INNOVATIVE PARTNERSHIPS

The Alliances in the CTA program include not only the five consortia with partnerships among universities, industry, and ARL, but also Army RDECs, as well as other Army and other Government Agencies (OGAs).

The Army RDECs and OGAs are invited to actively participate in the research program and to conduct research jointly with Alliance members. The annual research program plan is also cooperatively formulated by Consortium members and ARL with input from the RDECs and OGAs through participation on the Research Management Boards (RMBs) established for each Alliance.

The RMB partners are critical to identifying opportunities for transitioning CTA research results into their ongoing R&D programs. This transition is facilitated by a task order contract built into the CTA agreements. Numerous Army RDECs and OGAs have taken advantage of this contract mechanism to apply CTA research results to their technology development programs.

The CTA technology transition approach relies on collaboration and partnering of ARL, RDECs and RMB members. This team works with the technology user community to seek out transition opportunities and to demonstrate technologies mature enough for application.

LEADING EDGE TECHNOLOGIES

Highlights of CTA accomplishments to date include:

Advanced Decision Architectures

- Improved distributed planning activities via Collaborative Slide ANnotation Tool (CSLANT) during the Communications and Electronics Research, Development and Engineering Center (CERDEC) Joint Forces experiment.
- Enhanced Decision Architecture Research Environment (DARE) to improve situation awareness and control of robotic systems via cross-consortia collaboration with Robotics CTA.

Advanced Sensors

- Developed a new infrared sensor material for infrared sensors, which will provide benefits for size, weight, power, cost, and reliability and conducted a successful imaging demonstration of a mid-wave infrared focal plane array.
- Transitioned research on Micro Radar technology, which significantly improves the ability to detect, track and identify objects with remote sensors; this is being integrated with sensor systems now in use by U.S. Soldiers in theater.

Communications and Networks

- Developed protocols that enable secure mobile networks to be optimally configured and rapidly deployed.

- Transitioned methods to optimize use of network resources to improve mission effectiveness to the CERDEC Proactive Integrated Link Selection for Network Robustness (PILSNER) program.

Power and Energy

- Demonstrated the viability of Direct Methanol Fuel Cell (DMFC) for Soldier power and the rapid progression toward the FY08 M25 DMFC system designed to power the Future Force Warrior.

- Completed the design of a demonstration Micro Electrical-Mechanical Systems (MEMS) gas turbine engine and initiated device fabrication, taking a major step toward demonstrating the feasibility of a MEMS gas turbine generator for Soldier portable power use. Such a device would serve as a battery replacement for the Soldier, allowing a drop in energy system weight by a factor of 5-10, significantly impacting the load that a Soldier needs to carry.

Robotics

- Developed, proved, and transitioned to key military acquisition programs the core autonomous mobility technologies that enable unmanned vehicles to be sent on missions and observe, orient themselves, decide, and act in complex environments while requiring minimal Soldier control, ensuring that robots will operate as force-multipliers in the future battlespace.

- Conducted a thorough investigation of multi-modal, scalable Soldier Machine Interfaces and a variety of form factors that enable remote simultaneous command and control of multiple unmanned heterogeneous assets and support unmanned RSTA operations, enabling Soldiers to focus on battle tactics appropriate to small combat teams.

Plus :

- $738 M from other agencies placed on transitions contract
- 1800 refereed papers, conference presentations and proceedings
- 120 workshops, seminars, and short courses conducted

SUPPORTING ARMY TRANSFORMATION

The CTA program's value to the Warfighter is significantly enhanced when the enabling technologies that result from the basic research projects are exploited to their full potential. The identification of user champions through early and frequent collaborations and partnerships is a key component of the process for effective transition with defined entrance and exit criteria.

CTA researchers have participated in many key defense programs, such as Future Combat Systems (FCS), Future Force Warrior (FFW), DARPA Total Information Awareness and Warfighter Information Network – Tactical (WIN-T), and Adaptive Joint CISR Node (AJCN). Furthermore, each CTA member provides world-class laboratory facilities and testbeds for use by ARL and other CTA members. These facilities create tremendous leverage for the Army Science and Technology Programs.

From the cooperative program formulation through the collaborative research efforts, the CTA program is efficiently focusing the expertise of industry, academia and the U.S. Army Research Laboratory on enabling technologies and new military capabilities needed for Army Transformation.

Communications and Networks technology advances will improve Soldiers' battlefield situational awareness.

CTA

ADVANCED DECISION ARCHITECTURES

ADVANCED DECISION ARCHITECTURES

ADVANCED DECISION ARCHITECTURES CTA OVERVIEW

OBJECTIVES

The Advanced Decision Architectures Collaborative Technology Alliance is developing, validating, and transitioning new knowledge management and decision support technologies to provide the Warfighter a better understanding of the tactical situation, a better evaluation of courses of action, and more effective team communications. This will enable Warfighters to make better and timelier decisions and enhance their opportunity for success.

TECHNICAL AREAS

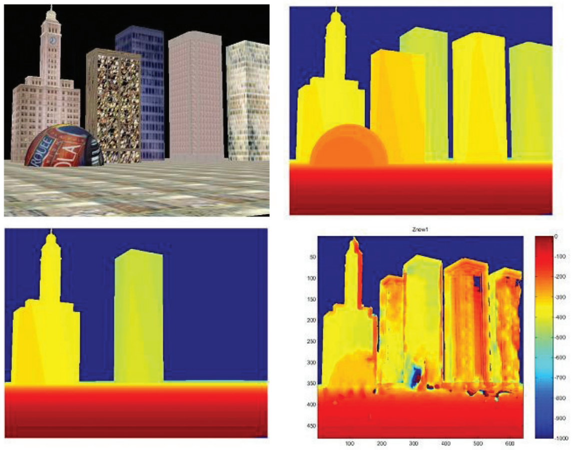
Cognitive Process Modeling and Metrics

Cognitive processes are modeled, both qualitatively and quantitatively. We research unobtrusive ways to quantitatively assess users' states in order to better support decision-making. Issues about trust, especially in relation to technology, are explored and modeled to understand the impact on performance.

Team Communication and Collaboration

Our goal is to create tools and intelligent systems that support collaborative decision making across distributed teams, allow decision makers to share data in meaningful ways, and to examine the impact of their decisions. We research how individuals and teams make decisions, assess situations, and interact with technology. This

ADA research on culture supports multinational interactions.



Depth maps support 3D modeling of urban terrain.

understanding is used to prototype and iteratively test and validate collaborative software-based tools with actual Army decision makers.

CONTEXT-SENSITIVE INFORMATION PRESENTATION

This research area represents the state of the art in presenting the right information to the Soldier at the right time. It includes haptic displays, multi-modal information presentation, and flexible displays. We research how the constraints in Future Combat Systems (FCS) (i.e., network limitations, bandwidth restrictions) will impact the ability of the Soldier to understand the situation and make appropriate decisions.

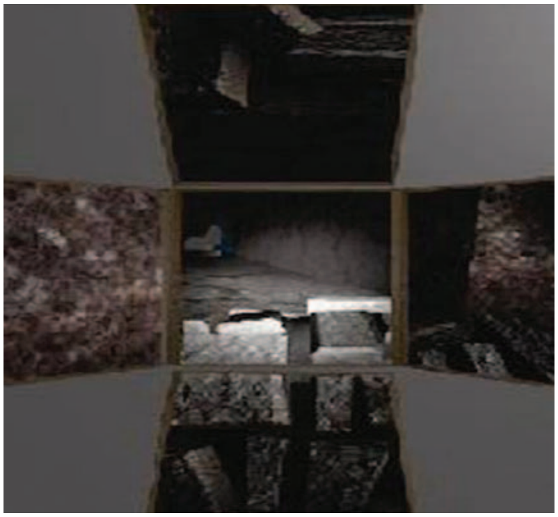
FUSION AND INTELLIGENT ARCHITECTURES

This task area focuses on the management of resources through information fusion and intelligent architectures. Commanders must manage the physical resources such as robotic sensors as well as the network itself and the communication links within it. We research architectures to help Soldiers reason about and understand the digital battlefield.

ACCOMPLISHMENTS

- Improved distributed planning activities via Collaborative Slide ANnotation Tool (CSLANT) during a CERDEC Joint Forces experiment.

- Enhanced Decision Architecture Research Environment (DARE) to improve situation awareness and control



Perspective-folding is an example of context-sensitive information presentation.

of robotic systems via cross-consortia collaboration with Robotics.

- Built a tool to help commanders visualize Command and Control (C2) structures, analyze effectiveness, and redesign the structure if necessary.

- Created a tool that successfully enumerates courses of action, filters out all but the most promising, and helps the decision maker visualize tradeoffs across the alternatives.

- Created haptic devices and guidelines for their use that can be used to silently communicate with Soldiers in the field.

- Developed a lightweight computational model of decision making that can be used to layer more human-like decisions in a complex, task network simulation.

PARTNERS

Full Partners

Alion, MA&D Operation

Klein Associates, a Division of Applied Research Associates, Inc.

SA Technologies Inc.

ArtisTech Inc.

The Ohio State University

Massachusetts Institute of Technology

Carnegie Mellon University

New Mexico State University

The University of West Florida

Associate Partners

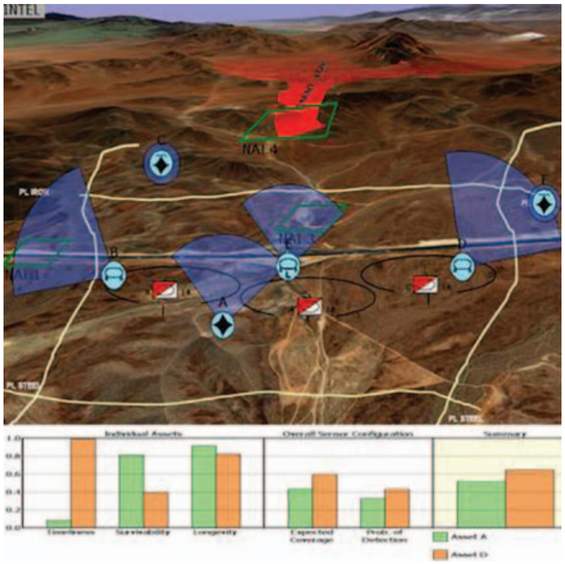
University of Central Florida

University of Maryland

Wright State University

University of Michigan

The Pennsylvania State University



Risk and uncertainty visualization help Soldiers understand the digital battlefield.

ADVANCED DECISION ARCHITECTURES

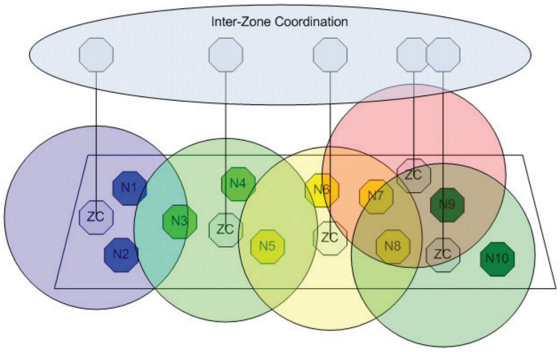
AGILE COMPUTING TO SUPPORT BATTLEFIELD INFORMATION REQUIREMENTS

DESCRIPTION

Agile computing is well suited for Future Combat Systems (FCS) environment due to the ad-hoc nature of the computers, networks, and sensors in FCS. Agile software agents can quickly react to changes in the environment and take advantage of transient resources. Moreover, agents can move themselves across systems over a network link. We are developing an agile computing infrastructure and user interfaces that enable optimal use of scarce computing and network resources and coordination of human-robot teams in FCS. The integrated communications framework will improve data routing and transport in tactical environments. We are extending this work by developing a policy and services to classify, tag, and facilitate information exchange between secret and unclassified domains.

We are exploring how agents and mobile code can be used in conjunction with autonomous vehicles in order to greatly improve the ability to task and reconfigure autonomous vehicles in the field, and to enable them to interact seamlessly with humans as team players. Agent technology provides a foundation for developing information retrieval and performance support tools.

An agile computing infrastructure enables optimal use of scarce computing and network resources.



Zone-level coordination removes bottlenecks in FCS networks.

ACCOMPLISHMENTS

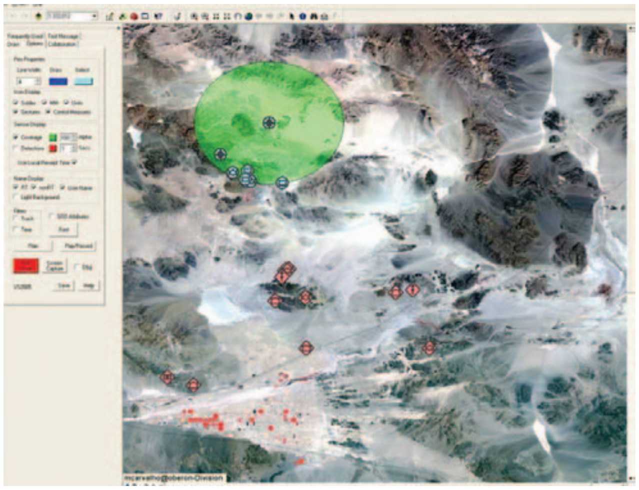
- A prototype agile computing infrastructure was built upon our existing Neurally Organized Mobile Adaptive Device (NOMADS) and Knowledgeable Agent-oriented System (KAoS) agent systems.

- We increased the flexibility of FCS by using software agents in the role of middleware and end-user tools. The Agile Computing FlexFeed Coordinator provided bandwidth-efficient, hierarchical distribution of data in the Warrior's Edge Horizontal Fusion Exercise.

- We subsequently evolved the middleware implementation to use a zone-based coordination approach, which removes the single point of failure and the bottleneck associated with a centralized coordinator.

- Mobile sockets (mockets) were created that compensated for Transmission Control Protocol (TCP) failures and provided keep-alives and connection loss detection. The mockets library was integrated with the KAoS policy and domain services library, allowing bandwidth utilization of applications to be controlled through KAoS policies. We enhanced the Mockets communication library by adding the capability to detect the network quality by estimating the Round Trip Time.

- We demonstrated a policy that distributes position updates sent by Tactical Object and Graphics (TOS) to Secret clients and Public clients. Secret clients were



In this policy-based filtering demonstration, allowed proximity to secret clients is set to 7000 m.

allowed to receive updates from all Secret and Public clients at all times. Public clients were allowed to receive updates of all Public clients, but only those of Secret clients that were within a range specified by the policy.

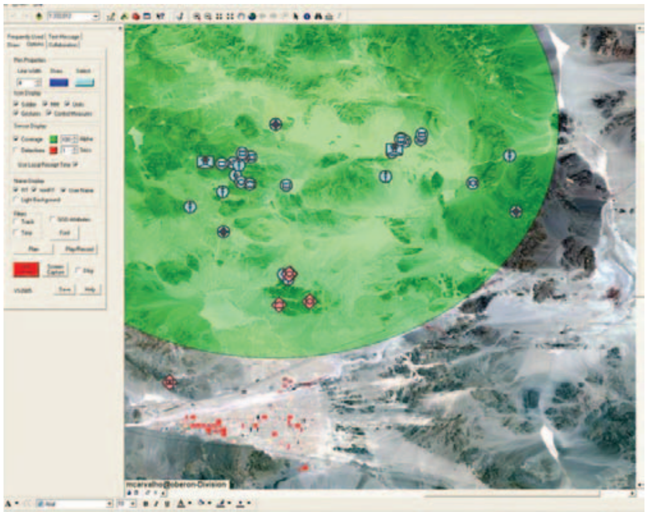
- Initial KAoS ontologies and reasoning mechanisms were developed to represent and construct influence diagram models on the fly, enabling context-sensitive policy adjustment. This supports human-agent teams in appropriately trading off authority and responsibility among various team members as they coordinate joint activity.

- We developed a peer-to-peer Instant Messaging application that is fully decentralized. This leverages the capabilities of the Group Manager. This capability will be evolved to support distributed collaboration services.

- An Urban Cordon and Search Scenario explored more complex policy-based filtering in conjunction with the capabilities of the agile computing infrastructure. The scenario is a laboratory exercise that involves two platoons executing a cordon and search of a specified building. Special Ops forces are nearby, though concealed from the two platoons. KAoS policy services will be used to control the resolution of Aerial images provided to the Platoon Leaders. Ontologies are used to reason about methods and sources obscuration in cross-domain information exchange.

PROJECT LEADERS

Mr. Niranjan Suri and Dr. Jeff Bradshaw, University of West Florida Institute for Human and Machine Cognition, Pensacola, FL



Allowed proximity to secret clients has been increased to 25,000 m.

ADVANCED DECISION ARCHITECTURES

ANALYSIS OF ORGANIZATIONAL STRENGTHS & VULNERABILITIES

DESCRIPTION

Today's Army Brigades (and tomorrow's Units of Action) are characterized by complex evolving missions, network-centric operations, joint or coalition collaborations, a limited number of personnel, and the need for rapid effective response. Information availability, mission complexity, and personnel changes can limit a leader's ability to track who knows what, who can do what, who is doing what, and who has worked with whom. We developed new statistical, analytical, and visualization techniques to support this "need to know," called the Organizational Risk Analyzer (ORA). ORA considers relations among humans, resources, knowledge, tasks and groups. Our goal is to enhance the ability of Army Units of Action to adapt rapidly to changing missions to support the commander by providing a dynamic birds-eye-view of who is doing what, when, and with whom. In support of this, we are developing dynamic network measures for assessing the unit of action's "organizational" health in meaningful terms.

The Organizational Risk Organizer considers relations among humans, resources, and knowledge.

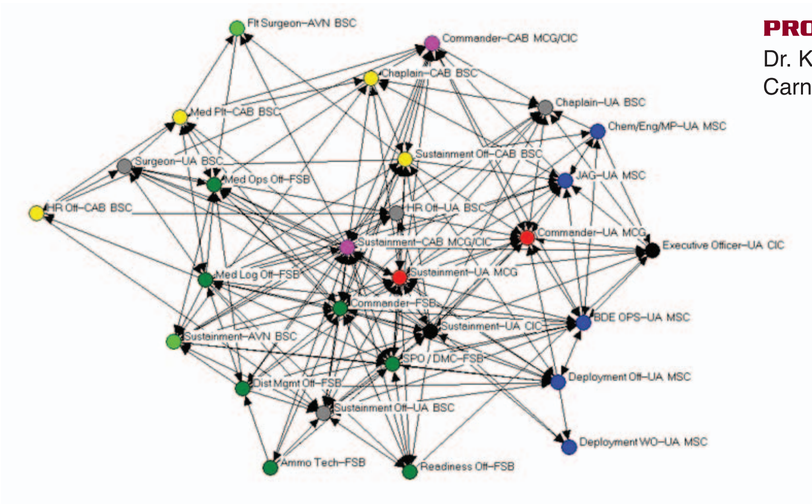
ACCOMPLISHMENTS

- We applied our techniques to collect, measure, analyze, and visualize data and then make recommendations about Command and Control (C2) structures in the Army Unit of Action and Unit of Employment effort. We adapted and evaluated ORA for assessing vulnerabilities and strengths in a unit's C2 structure under dynamic conditions.

- We collected, analyzed, and reported trends in a C2 staff to provide information that impacts vulnerability, performance, and adaptability. We used the analysis and visualization tools to examine the C2 structures that worked well in each setting. We then used ORA to design more optimal Command Control Communication Intelligence (C3I) structures.

- ORA was integrated with tools that Soldiers are already using (like Analyst's Notebook), accepting input from external sources and improving the visualization capabilities of the tool.

- Additional validation of social and knowledge network based measures of situation awareness was completed at the individual, dyad, and unit level. The focus was on knowledge of "what" is being done and "who is doing what." We also evaluated the correlation of situation awareness measures with other measures of training, social networks, and rank.



Analysis of a command and control unit show what is being done and who is doing it.

PROJECT LEADERS

Dr. Kathleen M. Carley and Dr. Cleotilde Gonzalez, Carnegie Mellon University, Pittsburgh, PA

- A mathematical formulation of key metrics for assessment of shared situation awareness at the team level was developed. All new and validated metrics were added to ORA, tested at Unit of Action (UA) battle lab experiment, and used at ARL with the J9.

- The validated metrics were incorporated into a simulation tool, Construct, to explore change in situation awareness over time. Construct can be used for near term prediction of change in situation assessment. Construct is callable from ORA.

- In order to map changes in the way in which the commander's intent is viewed, there is a need to extract networks from texts. We are expanding the text-mining tool, AutoMap, to rapidly code new raw text data so that such information can be contrasted with existing information. ORA can then rapidly identify how this new information changes the current assessment of the commander's intent.

- We recently increased the speed of text processing by 25 percent. In addition, the accuracy of entity extraction in the text analysis has improved to 96 percent accuracy.

ADVANCED DECISION ARCHITECTURES

APPLYING FLEXIBLE DISPLAYS TO WARFIGHTER NEEDS

DESCRIPTION

Flexible display technology, being developed at the Flexible Display Center at Arizona State University and other places, shows promise in terms of weight, ease of storage, and ruggedness. Our research is focused to ensure that human-centering and human-systems integration issues are considered as these displays mature. Such issues include traditional human factors issues of resolution, angle of look, definition, brightness, and ease of use. There are also issues of display size, which will likely constrain the types of data and the data formats that can be displayed in the Warfighter context.

Our goal is to develop an understanding of how the technology of flexible displays might be applied to Warfighter needs at the platoon level and below. In particular, we focused on how flexible displays can reduce the cognitive load of Soldiers.

Flexible displays show promise for tomorrow's Soldier.

ACCOMPLISHMENTS

- We created Mock-up flexible displays of a variety of data types including satellite images, maps, intent statements, and terrestrial photographs of urban environments.
- Created a cordon and search operation scenario in which to evaluate the flexible display mock ups. The scenario will be used in a study with ROTC students and experienced Officers in the Department of Military Science department at the University of West Florida.
- A detailed analysis of tasks in the Army Universal Task list was conducted in terms of ways flexible displays might be useful versus way flexible displays could hinder performance.
- During a Future Force Warrior (FFW) exercise, we collected survey data on how Soldiers envision using flexible displays. Our focus is on what the Soldier needs to see, when it is needed, and how flexible display capabilities can reduce the cognitive load.

Flexible displays offer ruggedness, easy storage, and low weight for situations like this.

We coordinated with Natick Labs to insure complementarity of their user survey approach and our test scenario. We found points where the Natick user survey data could improve our method, and points where our materials and tasks could help them generalize to a range of devices.

A collaboration was established with researchers at ARL/HRED-Ft. Benning. Ft. Benning ARL researchers will facilitate the involvement of experienced Warfighters in a first main study, to be conducted in FY07. The main study will investigate flexible display applications and issues of perspective and common ground.

PROJECT LEADER

Dr. Robert R. Hoffman, University of West Florida Institute for Human and Machine Cognition, Pensacola, FL

ADVANCED DECISION ARCHITECTURES

COGNITIVELY INSPIRED ADVANCED DECISION ARCHITECTURES

DESCRIPTION

The projects under this topic show how concepts such as situation awareness and expertise can be understood, formalized, and used to drive specific design recommendations. We computationally represent these concepts to support more intelligent pushes of information in a distributed fusion environment. We are creating automated (and partially automated) situation estimates at useful levels of abstraction. Automated information fusion can create "situation awareness" for autonomous vehicles, millisecond response defenses, and other such applications. Our advanced agent software architecture incorporates a computational recognition-primed decision making (RPD) model for assisting human teams in sharing information relevant to their decision makings, with an emphasis on agents that learn and adapt. Simulation-based techniques support the context-driven dissemination of sensor information in a distributed environment. These architectures will have a direct impact on how information technologies are designed and fielded. This ensures that the human will be able to keep up with the flood of information technologies that are driving Army transformation.

Cognitively-inspired architectures help Soldiers keep up with the flood of information technologies.

RPD-enabled agents can help the S2 and S3 deal with the 3 Block Challenge.

ACCOMPLISHMENTS

- Three partners collaborated to define a scenario and a task network model in Micro Saint to exemplify interactions between fusion processes and models of decision making. Our fusion engine and RPD-enabled Collaborative Agents Simulating Teamwork (R-CAST) decision agents were integrated into the DARE scenario in MicroSaint. A report describing these cognitively inspired architectures was submitted to CERDEC.

- An experiment was conducted with Army ROTC students regarding Recognition-Primed Decision Making (RPD-enabled) agents assisting S2 and S3 in dealing with 3 Block Challenges scenarios. The results demonstrated that C2 team performance, while still limited by the human cognitive capacity, could be largely improved when they were assisted by RPD-enabled agents capable of proactive information gathering/sharing and experience-based decision making. We elaborated the R-CAST approach to represent decision-making contexts for sharing relevant information.

- We built models of mission execution that demonstrate how representations of context based on cognitive principles can support information distribution on the battlefield. This was done by adding the capability to "pull" information that fits a context in addition to the capability to "push" information according to pre-set rules.

The Battlespace Terrain Reasoning and Awareness System can infer enemy intent.

- We visited the Army Corps of Engineers at Ft. Belvior to understand terrain abstractions used in the Battlespace Terrain Reasoning and Awareness system. This was part of an investigation of abstractions that may provide useful constraints for reasoning about enemy behaviors for inferring enemy intent.

- We successfully analyzed entity re-identification and tracking in terms of abductive inference, validating this analysis through implemented proof-of-principle systems for ground-based platforms. This used our diagrammatic reasoning capability developed under another research task.

- We developed strategies that help an abduction-based Fusion Engine to identify and recover from reasoning mistakes by revising previous conclusions under some circumstances. A report documented how an abductive reasoner can be designed to change its mind, and appropriately revise previous conclusions, when expectations are violated by unfolding events.

PROJECT LEADERS

Dr. B. Chandrasekaran and Dr. John Josephson, The Ohio State University Laboratory for Artificial Intelligence Research, Columbus, OH

Mr. Robert Winkler, ARL, Adelphi, MD

Dr. Walter Warwick, Alion, MA&D Operation, Boulder, CO

Dr. John Yen, Pennsylvania State University, University Park, PA

Simulation based techniques support distribution of information on the battlefield.

ADVANCED DECISION ARCHITECTURES

CONTINUOUS DISTRIBUTED PLANNING TOOL

DESCRIPTION

Distributed teams lose the advantage of face-to-face communication and gestures. For example, facial expressions conveying a puzzled look would be lost in an asynchronous environment. We addressed this shortcoming by helping teams detect and repair inadequate shared understanding. Collaborative SLide ANnotation Tool, or CSLANT, enables more effective one-way communication than he current state of the art. CSLANT allows team members to convey visually rich information about plans and dynamic battlefield conditions. Voice is synchronized with pointing gestures and dynamic map annotations via inexpensive and easily obtainable technology. This allows Soldiers to quickly sketch their thoughts.

By detecting and repairing shared understanding, CSLANT increases trust and motivation. Multiple empirical studies, observations, and beta tests have been conducted to assess the usefulness of the tool. As part of this process, we investigated how the communication medium influences what a person says and how they say it.

CSLANT improved situation awareness and understanding of intent.

CSLANT helps Soldiers communicate mapboard information when teams are geographically distributed.

ACCOMPLISHMENTS

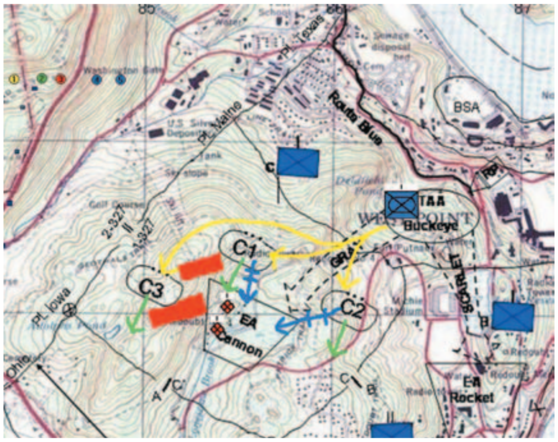
- An empirical study showed that CSLANT improved Situation Awareness (SA) and understanding of intent by 47–65 percent as compared with the traditional operations order format.

- Soldiers were able to use CSLANT effectively, even with a mere 15 minutes to become familiar with the tool. This is because CSLANT takes advantage of "natural communication" such as pointing and summarizing.

- CSLANT was integrated with CERDEC's Web C2 Portal to create a tool that enhances shared SA and supports both synchronous and asynchronous communications during continuous adaptive planning activities.

- CSLANT improved distributed planning activities during a CERDEC Joint Forces experiment. It helped identify and correct miscommunications resulting from live briefings. CSLANT also supported the sharing of important knowledge across units.

- Extensive beta-testing was done by various organizations in the Army as well as contract organizations including: Battle Command Battle Lab (BCBL)-Leavenworth, USMA, United States Air Force Academy, CERDEC, ARL, Carnegie Mellon University (CMU), Naval Postgraduate School, and MITRE.



CSLANT provides asynchronous visual and audio communication.

- We investigated how the communication medium influences what people say and how they say it. This was accomplished through observing exercises (The Ramp-Up to a 1st Cavalry Division Warfighter Exercise, a 1st Cavalry Division Warfighter Exercise, and a 1st Brigage/1st Calvary Division National Training Center Rotation) and through data collection and analysis of experiments at BCBL-Fort Leavenworth (Concept Experimentation Program, Limited Objective Experiment, and the Omni Fusion Build 2).

PROJECT LEADERS

Dr. Phil Smith, The Ohio State University, Columbus, OH

Mr. Rich Kaste, ARL, Adelphi, MD

The tool was improved by observing multiple Warfighter exercises.

ADVANCED DECISION ARCHITECTURES

DECENTRALIZED ISR AND COMMUNICATIONS FOR WIRELESS SENSOR NETWORKS

DESCRIPTION

With new sensor technologies and communication networks being developed for the battlefield, the commander and his staff must integrate and be aware of more system information than ever before. Technologies from several consortia are being pulled together to develop an integrated fixed and mobile networked Intelligence Surveillance Recognizance (ISR) system. The ADA researchers are creating a set of information displays which show how the current network status and operational efficiency will affect decision-making and planned intent. We are also developing advanced prototype software to support dynamic ISR tasking and interpretation that is capable of fusing information to estimate threats and appropriately direct warnings. These displays will help optimize the commander's awareness of both the situation and the health and status of the ISR network. This task is being conducted in the context of an urban evacuation scenario.

User interface to collect, analyze, integrate, and fuse incoming sensor data.

ADA researchers are developing software to estimate threats and direct warnings.

ACCOMPLISHMENTS

- An urban evacuation scenario was developed with emphasis on the automated and human fusion involved throughout the mission.

- A goal-directed task analysis for Company Commanders was conducted, focusing on sensor and communication network information requirements. This determined what information the commander needs to be aware of and what information should be fused to a higher level. We determined how coarsely to present information to decision makers so they can effectively process and use that information.

- We designed a User Interface and framework (based on SA Technologies' Synergy display suite) for the cross consortia project demonstration, showing how the project's goals to collect, analyze, integrate and fuse the incoming sensor data would be transformed into a usable format to support the Commander's Intent.

- We focused on the process by which data from the multimodal sensor array could be used in conjunction with other sensor information (such as video sensors) to verify that a vehicle was moving at a certain speed into an area of interest. The end result was an alert to the Commander in support of one of his Commanders Critical Information Requirements (CCIR).

ADA created displays for retasking the network.

- The User Interface incorporated both sensor and communication networks. We created displays for different sensor modalities, communication networks, and re-tasking the network. This was driven by a user-centered design that ensured the systems supported the needs and capabilities of the Warfighter (physical, perceptual and cognitive), rather than simply provided lots of data.

- We specified how the analysis of information requirements can be used to drive automated fusion for behavior recognition, threat warning, and other aspects of “higher-level fusion,” to support small unit tactical decision making, as well as decision making at higher echelons. At higher echelons, where the analysis of information requirements, and the tasking of ISR assets, is done explicitly, and where computers and communication resources will be used as a matter of course, the knowledge needed for automated fusion can be captured as a side effect of the analysis and tasking. At lower echelons, standing orders to sensor networks can be used to drive the capture, in advance of deployment, of at least portions of the needed knowledge.

- A prototyped software module was developed to translate Commander’s Intent to ISR tasking. This demonstrated the capability for automated fusion to support higher-level SA for command decision making. It also showed that the software was capable of fusing much more information than possible for unaided humans.

- We developed an abduction algorithm for higher-level fusion that used domain and situation knowledge to produce threat warnings from indicators.

PROJECT LEADERS

Dr. Cheryl Bolstad, SA Technologies, Marietta, GA

Dr. John Josephson and Dr. B. Chandrasekaran, The Ohio State University Laboratory for Artificial Intelligence Research, Columbus, OH

Dr. Mike Strub, ARL, Adelphi, MD

Automated fusion can recognize threats and support small unit tactical decision making.

ADVANCED DECISION ARCHITECTURES

DECISION ARCHITECTURES RESEARCH ENVIRONMENT

DESCRIPTION

The Decision Architectures Research Environment (DARE) is an experimental environment in which CTA partners can conduct research into team collaboration and effectiveness. It enables us to identify what technology and human factors solutions work well and which need to be improved. It allows us to rapidly transition technologies that bear fruit to major Army programs such as INTEL Operations at Intelligence and Security Command (INSCOM), Future Force Warrior, and the Future Combat System.

DARE enables partners to integrate and test technologies on ARL platforms within the context of relevant and realistic scenarios. The DARE software architecture consists of different layers including communications, data transmission, and data presentation. These layers are united through communication protocols, enabling interplay of multiple components, and providing “plug and play” capabilities. This software is then used to integrate ADA technologies with other ARL Soldier equipment, and to simulate the combined effects on Soldier performance in a realistic scenario. We have rapidly integrated several CTA technologies, including agile software agents, diagrammatic reasoning, collaborative technologies, multimodal technology, and robotic control. Upon integration, the technologies become a part of ongoing ARL programs where experiments with Soldiers are conducted and the value of the technologies can be assessed.

The power of DARE was demonstrated in a simulated company-level operation.

The same picture can be displayed on different sized platforms.

ACCOMPLISHMENTS

- A test bed architecture was developed utilizing information from the Warrior Edge program. The power of DARE was demonstrated through a simulation of a company-level cordon and search operation of an urban area.

- Integrating the functionality of collaborative ADA technologies allowed distributed teams to develop and communicate mission plans. A Company Commander can use CSLANT to effectively present his initial plan to distributed Platoon Leaders. Shared Displays and Digital Ink allow the platoon leaders to view the annotated mission plan on their hand-held displays, add annotations, and distribute their annotations to other leaders. This utilization of drawing, chat, and multimedia capture is a fundamental advantage for distributed plan collaboration.

- Insights from a joint project on robotic control were used to realistically control the robots and communicate robot-provided information.

- ADA agile software agents were integrated to form the backbone of the system. The agile software agents provide alerts, monitor sensor data, monitor system health, and provide a distributed processing paradigm.

- The fusion engine developed by The Ohio State University was successfully integrated, validating the viability of the architecture.

- A tactile display was built into the Soldier system. Vibrations can be used to alert the commander and

A DARE Deployed Research Operational Platform was also delivered to Alion researchers in support of Advanced Decision Architectures research on team communication in human-robotic teams. This configuration enables the utilization of Digital Ink and OSU s Collaborative SLide Annotation Tool (CSLANT) in experiments conducted utilizing the Rainbow Six game engine.

PROJECT LEADERS

Mr. Sean McGinnis, ArtisTech, Fairfax, VA

Mr. Robert Winkler and Mr. Tim Hanratty, ARL, Adelphi, MD

Ms. Susan Archer, Alion, MA&D Operation, Boulder, CO

draw his attention. In addition, different vibrations can be used to communicate different messages when the commander is not looking at the map.

This same picture can be displayed on several differently-sized commercially available platforms (i.e., tablet, PDA, cell phone).

The Operation Order (OPORD) was presented via a Concept Map, demonstrating that basic research findings can be showcased as well.

DARE was expanded to support multiple experimentation efforts. A DARE Deployed Research Operational Platform (DROP) and DARE Console were developed to empower collaborative research. This graphical user interface (GUI) application supports rapid setup and execution of DARE experiments with a variety of user-specified eXtensible Markup Language (XML) defined configurations. The DARE Console displays all executing DARE Agents currently residing on a single platform, facilitating the rapid diagnosis and repair of deployment and integration issues.

A DARE DROP was successfully deployed to Alion in support of research on Human-Robotic Interaction as part of the Robotics CTA. This configuration of DARE supports the utilization of MIT s tactile array through the General Dynamics Robotic Systems Soldier-Machine Interface (SMI) C2 System. The SMI-DARE DROP supports an experiment studying the utilization of tactile cues in human-robot interaction.

Digital Ink in DARE allows graphical sharing of information.

ADVANCED DECISION ARCHITECTURES

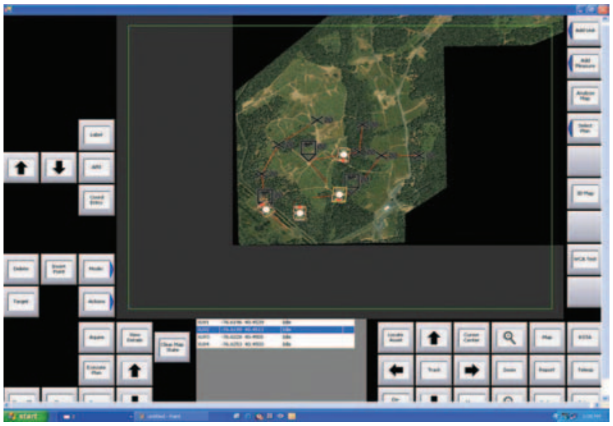
EVALUATING INTERFACES FOR NEW SYSTEM DESIGNS

DESCRIPTION

It is important to predict the effectiveness of operator control interfaces before they are actually developed. We are developing a software tool that allows system developers to evaluate the efficiency and effectiveness of an interface design by simply sketching out the interface graphically. This capability is enabled through the integration of a cognitive modeling framework with a traditional human-system integration modeling paradigm so that detailed predictions about the possible cognitive errors that might result can be made early in the design of a human-computer interface.

The tool, GRaph-Based Interface Language (GRBIL), takes a graphical description of an interface and automatically generates an Adaptive Control of Thought – Rational (ACT-R) cognitive model of the user interacting with an Improved Performance Research Integration Tool (IMPRINT) task network model of the system. GRBIL has a modern, commercial quality look and feel and potential users can interact directly with the graphical user interface. This is an effective method for evaluating system interfaces, detecting potential errors and inefficiencies, and identifying alternative system designs. It can be used to predict a Soldier's ability to effectively control multiple unmanned vehicles.

GRBIL can be used to evaluate advanced interfaces.



ADA modeled the use of the Operator Control Unit being developed in the Robotics CTA.

ACCOMPLISHMENTS

- An integrated prototype was developed that automatically generates IMPRINT and ACT-R models directly from user input. An extended prototype GRBIL tool successfully ran multiple Experimental Unmanned Vehicles simultaneously.

- We built an integrated model of an operator interacting with the prototype operator control unit (OCU) for the ARL Experimental Unmanned Vehicle being developed in the Robotics CTA. We then generalized the integration to accommodate any IMPRINT-ACT-R model.

- The functionality and output of the prototype tool were validated.

- In an effort applicable to the Robotics CTA, we developed a link to Autonomous Vehicle Operator Span of Control Evaluation Tool (AVOSCET), a tradeoff analysis tool which ultimately determines how many unmanned systems a Soldier or a crew can control at one time. We built ACT-R models of Operator Control Unit navigation initiated by AVOSCET models. The results were used to evaluate alternate system designs and make recommendations regarding system design and operator assignments.

- GRBIL has been integrated with other outside software that provides information to the GRBIL cognitive model or the IMPRINT environmental model. The current

Results were used to evaluate unmanned system designs and operator assignments.

PROJECT LEADERS

Mr. Rick Archer, Alion, MA&D Operation, Boulder, CO

Dr. Laurel Allender, ARL, Adelphi, MD

GRBIL tool uses the Weapon System Mapping Service (WSMS) for map functionality. WSMS is a defined standard developed by the Tank Automotive Research, Development & Engineering Center (TARDEC) within the Joint Technical Architecture – Army and is specified for use in embedded and/or real-time Army weapon system programs/applications. The Weapon System Mapping Service (WSMS) provides for the presentation of map and geo-referenced graphical elements within weapon system applications.

- The prototype tool uses a technique known as model tracing to catch errors. The tool looks ahead at the action that the simulated operator is about to make and determines whether or not that action is correct. If it will result in an error, that information is stored in a results file and the simulated operator is then diverted to the correct action. The error is noted but does not actually occur.

- We are adapting the model code to integrate GRBIL with Diagrammatic Reasoning functionality to perform spatial reasoning (e.g. collision detection) with unmanned vehicles in the Operator Control Unit (OCU) task. Diagrammatic Reasoning is another Advanced Decision Architectures product.

GRBIL uses the Weapon System Mapping Service to provide geo-referenced graphics.

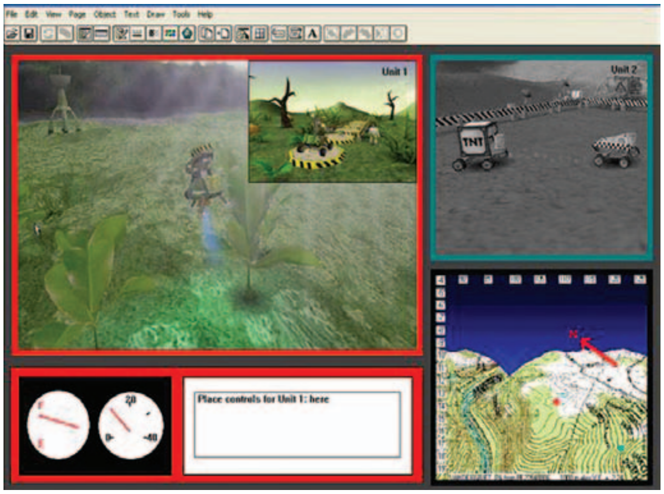
ADVANCED DECISION ARCHITECTURES

HUMAN-ROBOT INTERACTION

DESCRIPTION

Unmanned vehicles will be critical to the battlefield of the future. To fulfill this promise, we are researching how to increase integration and coordination of unmanned vehicles into the military mission. ADA researchers found that the major issues in human-robot interaction include difficulty in robot localization, lack of situation awareness on robot situatedness in complex environments, lack of integrated data presentation, and the effort required to perform multi-dimensional robotics tasks. Based on an understanding of these challenges, we are iteratively designing and prototyping interface concepts and testing them in the context of realistic military scenarios.

We are empirically investigating the interface requirements for control when multi-tasking or working within limited bandwidth. We are also investigating the impact of technology and team configuration (e.g., co-location) on reconnaissance mission. The products include a prototype interface for controlling and monitoring one or more robots, prototyping tools for human-robot interfaces, simulation environments for assessing military team performance, and a better understanding of the skill levels required for unmanned vehicle operators.



Visualizations to aid the control of multiple robots.

Soldier operating the Raven unmanned aerial vehicle (UAV) in Afghanistan.

ACCOMPLISHMENTS

- User interface concepts were developed and evaluated to help Unmanned Ground Vehicle (UGV) operators develop and maintain situational awareness (SA). The concepts were developed based on a goal-directed task analysis of critical goals and SA elements in a robot-assisted minefield breach.

- We developed a robust empirical framework for designing an interface to control multiple robots. This was used to develop visualizations related to navigation, multiple views, and status information. Interfaces were also developed for the UGV controller.

- Over 25 observational and experimental studies were conducted in the areas of multi-tasking and control of multiple robotic systems.

- We demonstrated the impact of collaborative technology and team configuration on the ability of the team to conduct a mission using unmanned vehicles. There were performance advantages to being co-located. These advantages persisted if one aspect of co-location was eliminated (i.e., face to face talk, visual image sharing, sharing the same view of the environment) but not if two aspects were eliminated.

The videogame Ravenshield was used to study team communication.

- A Virtual- and Mini-Robotics Lab was developed at New Mexico State University.

- Mapping capabilities were developed to support spatial visualization of the robot path through the environment.

- Empirical studies were conducted to determine the impact of communication latency on navigation performance at different levels of automation. Results showed that increasing the level of automation was an effective means of combating the negative effects of communication latency. Increasing the level of automation did not degrade situation awareness.

- A set of experiments suggested that displays that show motion may lead viewers to misestimate distances in a variety of situations. Special purpose displays need to be designed when operators need accurate values for distances.

- We investigated control strategies for operating and monitoring multiple robots. Results indicated that control mode affects operator navigation performance as well as the ability to develop high levels of situation awareness.

PROJECT LEADERS

Dr. Doug Gillan, New Mexico State University, Las Cruces, NM

Ms. Patricia McDermott, Alion, MA&D Operation, Boulder, CO

Dr. Jennifer Riley, SA Technologies, Marietta, GA

Dr. Laurel Allender and Mr. Michael Barnes, ARL, Adelphi, MD

A Soldier uses an interface to control a small unmanned ground vehicle.

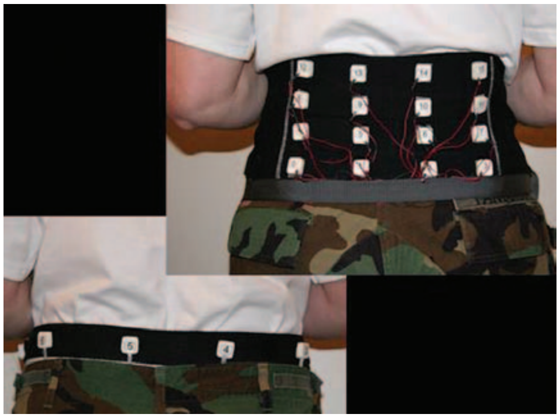
ADVANCED DECISION ARCHITECTURES

MULTIMODAL TECHNOLOGIES

DESCRIPTION

Our research focuses on tactile feedback systems that can be worn under a uniform either on the torso, arms, or legs and do not impede limb movements. The goal is to develop wearable haptic displays that present information about orientation, direction of movement, or threat location to a Soldier in the battlefield. The tactile modality provides an additional sensory communication channel that is generally underutilized. Our tactile displays are being evaluated as navigation aids and cues to assist in 3D sound localization. Tactile displays can also be used to remotely monitor Soldier vital signs such as heart rate, respiration rate, and skin temperature.

Tactile displays enable silent communication of simple commands and warnings that can be responded to immediately (e.g., stop, go, proceed slowly, yes, no) even when out of visual range. We are researching which tactile patterns are reliably identified and on which body site the patterns are most easily perceived. The displays are being incorporated into multi-modal platforms to support timely and effective information sharing through multiple media and modalities. In many areas of Army operations, multi-modal interfaces can effectively increase the information processing “bandwidth” of the Soldier.



Tactors arrayed on the torso and belt.

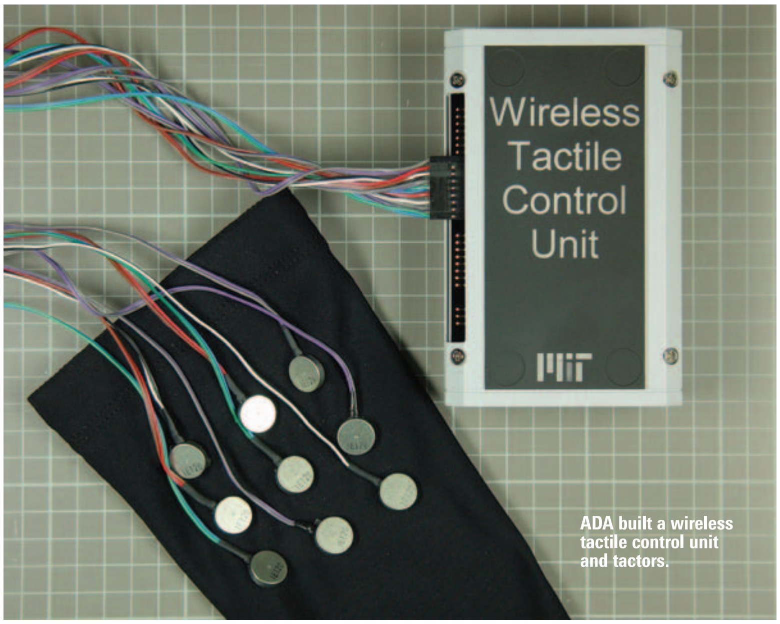
ACCOMPLISHMENTS

- We designed and fabricated a small, easy-to-control tactor array and circuit board that produces vibrations on the skin that are readily perceptible. In conjunction, we built a low-power, lightweight, non-invasive wireless Physiological Sensor System to measure heart-rate and respiration rate of the Soldier in the battlefield. We have made use of one of the technological innovations of researchers in the Institute for Soldier Nanotechnology at MIT to build a new type of respiration-rate sensor.

- Through experimentation with Soldiers, we identified a set of tactile patterns that can be perceived and interpreted with over 95 percent accuracy on the torso.

- We built a computer-based multimodal platform that presents multiple participants with a shared dynamic top-down view of a battlefield and enables them to exchange information with other human and machine agents via the visual, auditory, and tactile channel. This platform supports co-located and remote synchronous communication and coordination in the context of simulated battlefield operations.

- Using the multimodal platform, we documented natural patterns of modality usage and integration in a longitudinal study with battle scenarios. Participants developed highly selective and effective strategies for exploring and combining modalities to support a variety of coordinated functions, including timesharing, disambiguation, redundancy, and synergy.



ADA built a wireless tactile control unit and tactors.

Interface used in the multi-modal platform.

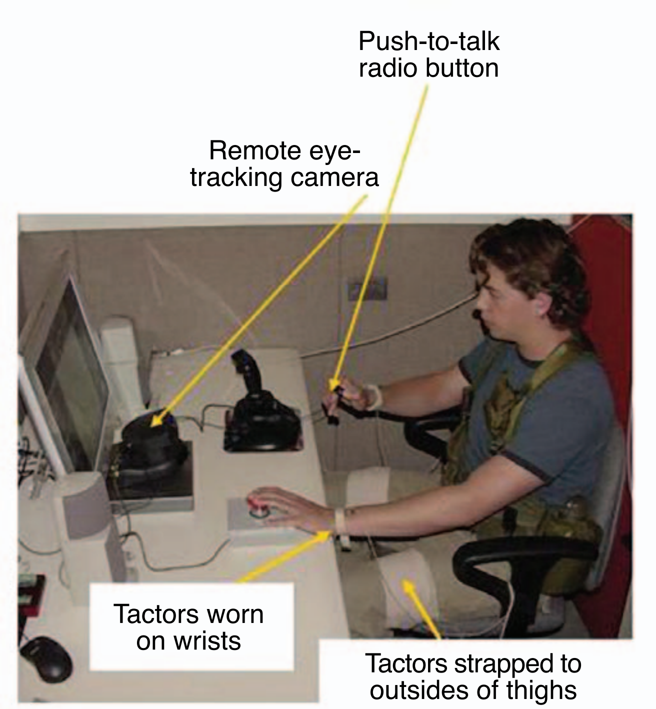
- We conducted empirical studies of cross-modal interactions between vision, audition, and touch to determine how to best coordinate the simultaneous, sequential, and adaptive use of various sensory channels. The findings were incorporated into an initial framework and guidance for human interface with vision, audition, and touch for problem-solving and decision making on the battlefield.

- A set of seven arm and hand signals used by Ground Forces was converted into tactile patterns that were presented using the MIT tactile display. An experiment was conducted with 15 different tactile patterns to determine how many could be accurately recognized. Despite the relatively large number of different patterns, subjects experienced little difficulty in identifying the tactile patterns and achieved a mean score of 98 percent correct (range: 89-100 percent). These patterns provide the basis of a tactile vocabulary that can be evaluated in field settings.

PROJECT LEADERS

Dr. Lynette Jones, Massachusetts Institutes of Technology, Cambridge, MA

Dr. Nadine Sarter, University of Michigan, Ann Arbor, MI



ADA built a multimodal platform to research cross modal interactions.

ADVANCED SENSORS

ADVANCED SENSORS

ADVANCED SENSORS CTA OVERVIEW

OBJECTIVES

The Advanced Sensors CTA (ASCTA) program is focused on research to dramatically increase sensor performance, enhance sensor utility and develop advanced techniques to combine data from many sensors into meaningful information for the Soldier.

In particular, ASCTA's goal is the development of affordable sensors and power-efficient signal processing to enable strategic dominance across the entire spectrum of operations. Through the development of these technologies, the output of ASCTA research will enable: (1) persistent sensing for unprecedented situational awareness and understanding; (2) accurate, all-weather, beyond-line-of-sight detection, tracking, and identification through multimodal networks of sensors; and, (3) timely and reliable information through networked multi-sensor information fusion.

TECHNICAL AREAS

ASCTA is focused into three broad technical areas of research; Micro Sensors, Electro Optic (EO)/Infrared (IR) Smart Sensors and Advanced RF Sensors. The goal is to focus on next generation sensors that minimize size, weight, and power to support Soldiers at the platoon or below echelon as envisioned by the Future Combat System.

ACCOMPLISHMENTS

Microsensors

This technical focus area researches the theory, algorithms, and sensor improvements needed to enable autonomous collection, processing, and control of information from networked heterogeneous microsensors. Examples include:

- Robust, scalable multi-sensor fusion over constrained communications bandwidth networks.

- Affordable detection, classification and tracking of multiple ground targets (people and vehicles) in high clutter environments.

- Automated/aided sensor network configuration and management so that a wide area can be covered with minimum support from the Warfighter.

- Analysis of networked microsensors for the selection of sensor types and numbers, sensor improvements, architectures and low energy signal processing.

EO/IR Smart Sensors

This technical focus area researches novel sensors and sensor component technology. Examples include:

- High performance, higher operating temperature IR detectors to provide effective fire control in diverse battlefield conditions.
- Active/passive imagers to enable highly integrated fire control in a compact form factor extending identification range and allowing the Soldier to act first.
- Hyperspectral Imaging (HSI) to enable target detection under low contrast and camouflage.

Advanced RF Sensors

Advanced RF Concepts area concentrates on high payoff technologies that will have an impact on a wider range of RF systems of interest to the Army, including microsensors, radar and communications.

- Enabling components for low cost multifunction RF systems that integrate radar, communication, combat identification, and electronic warfare/signals intelligence functions.
- Propagation and scattering studies and phenomenological data collection for multistatic RF systems that enable covert radar operation.

PARTNERS

ASCTA is comprised of leading-edge researchers in areas directly relevant to Microsensors and Microsensor Processing from both academic and industrial organizations together with the ARL.

ASCTA is led by BAE Systems and includes:

Clark Atlanta University
Georgia Institute of Technology
Massachusetts Institute of Technology
University of Florida
University of Illinois at Chicago
University of Maryland
University of Michigan
University of Mississippi
University of New Mexico
DRS Infrared Technologies
GE Security
General Dynamics Robotic Systems
Jet Propulsion Labs
Northrop Grumman

ADVANCED SENSORS

ACTIVE/PASSIVE IMAGING ARRAYS FOR NEXT GENERATION FIRE CONTROL SYSTEMS

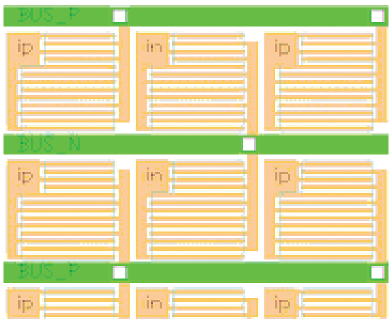
DESCRIPTION

Long range, accurate, inexpensive and robust targeting systems are critical to providing technology overmatch to our Soldiers on the battlefield. In pursuit of affording the Warfighter the ability to “see first, shoot first, and finish decisively,” ASCTA has been developing the enabling technology for next generation targeting systems. The key tenets of our research are:

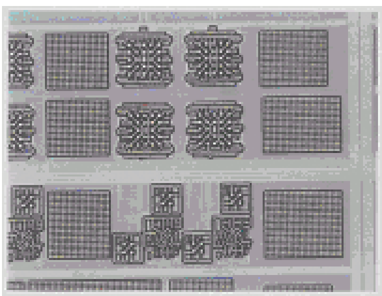
- Reconnaissance intelligence surveillance and target acquisition (RISTA) sensors that combine a wide field of view passive 2D imager with an active laser radar 3D imaging for confirmation and positive ID that is robust to foliage and camouflage due to separate returns from targets, foliage, camouflage nets, ground, etc.

- High power and high beam quality eye-safe (1.5-micron to 4.0 micron) lasers for ladar sources to provide higher resolution imaging at greater distances.

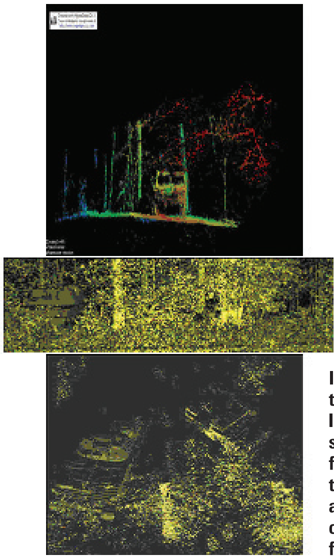
- New readout integrated circuits for active imaging focal plane arrays (FPAs) to enable an integrated active/passive readout integrated circuit. With a single large format FPA for active/passive imagery, a more compact, automatic alignment, reduced cost targeting system is possible. The ability to passively and actively image through a common aperture using a common focal plane array will enable a multifunction fire-control system leading to significant operational advantages such as:



Active Imaging MSM arrays.



Active ROIC pixels.



Images showing the power of a ladar sensor to separate targets from clutter. The top figure shows a ladar image collected in the field.

- Same field of view in both passive and active modes.

- No scanning required for active sensing.

- Reduced requirements for pointing accuracy and stabilization.

- Automatic bore-sighting capability between passive and active sensors.

- Concurrent passive infrared imaging with active 3-D imaging.

- Ability to image many targets per second since only the source needs to be slewed to the new target.

ACCOMPLISHMENTS

- Highly sensitive, highly uniform 32 X 32 metal semiconductor metal (MSM) gallium antimonide (GaSb) active arrays for active imaging have been developed for the ARL chirped amplitude modulation ladar at both eye-safe and non eye-safe wavelengths.

- World’s first mode locked eye-safe (1.55 micron) laser on a GaAs substrate was demonstrated. This innovation

500Å	GaAs
18000Å	$Al_{0.33}Ga_{0.67}As$
2050Å	GaAs
220Å	GaNAs
80Å	$Ga_{0.6}In_{0.38}N_{0.03}AsSb_{0.027}$
3.94Å	GaNAsSb
220Å	GaNAs
18000Å	$Al_{0.33}Ga_{0.67}As$
3400Å	GaAs buffer
N^+ GaAs Substrate	

Cross-section of a gallium indium nitride arsenide antimonide (GaInAsSb) quantum well material structure for mode-locked semiconductor lasers.

is significant due to the low loss waveguides possible in the GaAs/AlGaAs material system and promising optical medium due to highly strained quantum well.

- World's first active imaging readout integrated circuit.
- 8x8 small active/passive arrays were designed and fabricated.
- First-ever 8x8 active small readout integrated circuit was developed and fabricated.
- 32x32 gallium antimonide/indium arsenide (GaSb/InAs) MSM arrays were designed and fabricated.
- Demonstration of the world's second reported quantum dot vertical cavity surface emitting laser.

PROJECT LEADERS

Parvez Uppal, BAE Systems

Dan Carothers, BAE Systems

Barry Stann, ARL

Prof. Kevin Malloy, University of New Mexico

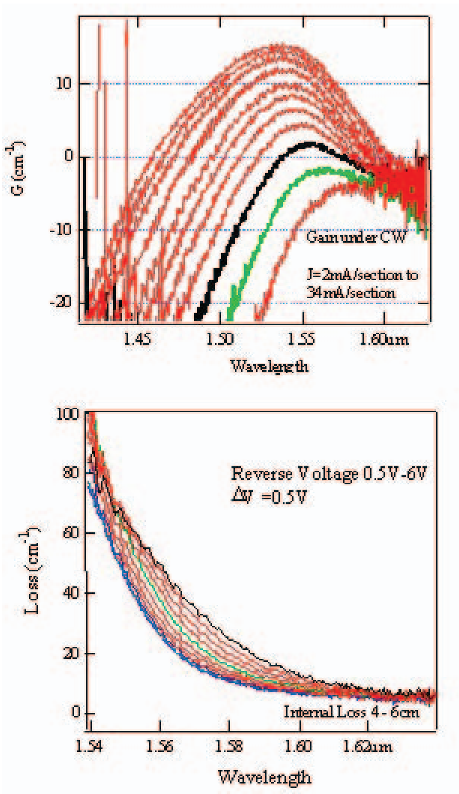
Keith Aliberti, ARL

Prof. Luke Lester, University of New Mexico

Bill Ruff, ARL

Prof. Fouad Kiamalev, University of Delaware

William Lawler, ARL



Absorption and loss curves indicate that GaInAsSb mode locked lasers are very promising for ARL's chirped amplitude modulation ladar applications as they offer higher power, higher modulation frequency, eye-safe wavelengths, and simpler implementation. Mode locking was achieved without the use of any passive waveguides.

ADVANCED SENSORS

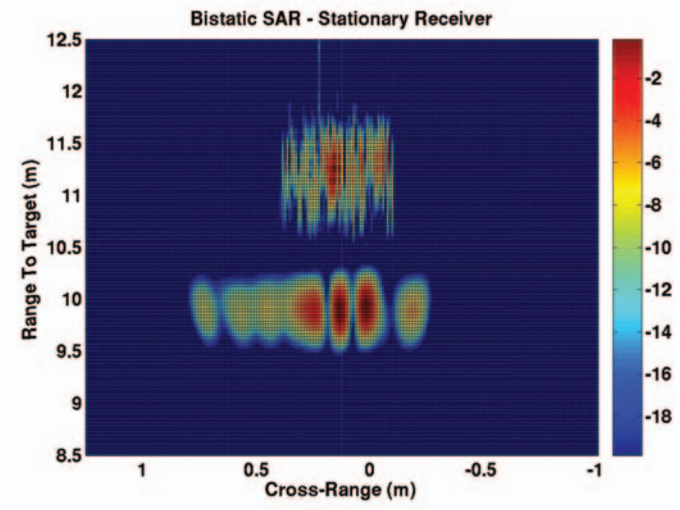
BISTATIC RADAR FOR SILENT AND COVERT DETECTION AND CLASSIFICATION

DESCRIPTION

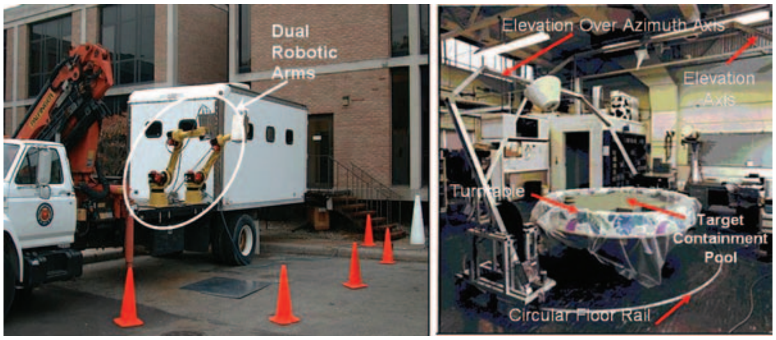
The phenomenology of bistatic radar offers a significant benefit for battlefield RF systems, enabling separation of emitters and collectors and greatly increasing survivability. This research is focused on developing an understanding of bistatic signal scattering from various types of terrain and over a wide range of illumination and scattering directions. Such a knowledge base is a crucial first step towards the development of bistatic radar systems. These next generation bistatic sensors can moreover be used to derive additional information about the target over prolonged surveillance. For example, multiple "silent" (hence, more secure) receivers mounted on low profile, mobile vehicles can be coupled with a single, remote transmitter and used to image and detect targets embedded in a complicated radar scene, benefiting the Soldier by:

- Providing the small unit commander with over the horizon radar for situational awareness without revealing his position.

- Reducing the power burden on the user, who operates in a receive-only mode.



Target detected with bistatic return in presence of clutter.

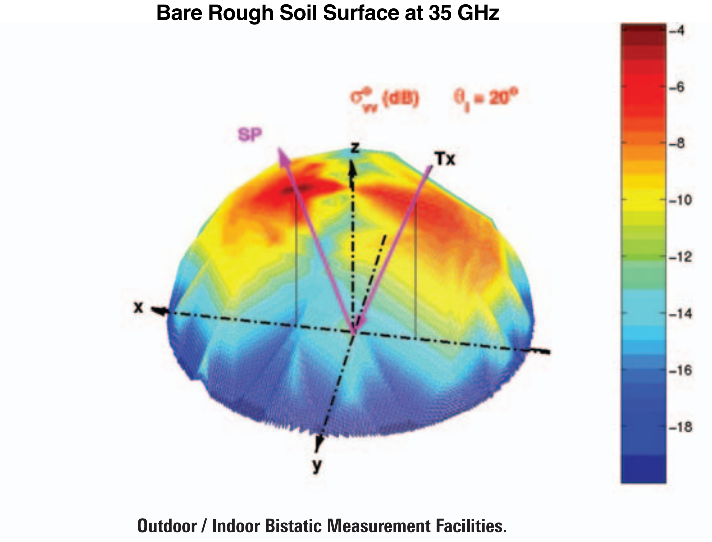


Bistatic Radar Scenario.

ACCOMPLISHMENTS

Towards this objective, a series of indoor measurements were conducted on rough soil surfaces using 35-GHz polarimetric, bistatic, instrumentation radar in order to characterize the radar response of clutter over the entire upper hemisphere for different illumination angles. The statistical nature of the bistatic return and the angular dependence of various polarimetric quantities, such as the co-polarization ratio, the cross- to co-polarization ratio, and the correlations between various polarized returns were determined.

As part of this effort, custom hardware was developed, including a unique outdoor, mobile, bistatic measurement facility for clutter characterization and synthetic aperture radar (SAR) imaging applications. The system, comprised of a coherent, polarimetric transmitter and two receiver modules operating at 35-GHz and mounted on two robotic arms atop a truck bed, is used to measure the polarimetric bistatic radar return from a wide range of clutter surfaces.

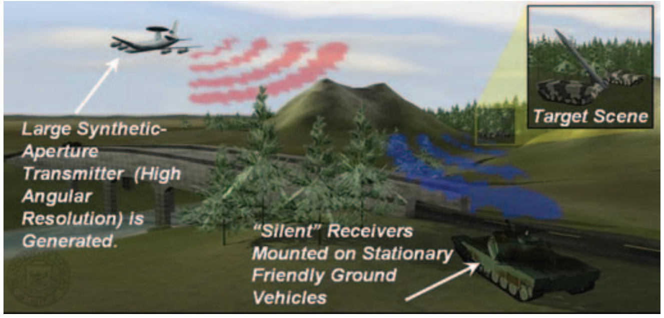


Outdoor / Indoor Bistatic Measurement Facilities.

Critical Element: Bistatic scattering data base for various terrain and environmental conditions.

Conclusions derived from these measurements were used to first identify bistatic configurations and polarimetric detection features. The ability of millimeter wave bistatic radar to detect low-flying, low radar cross section (RCS) projectiles/vehicles was then experimentally verified in a laboratory setting.

The tangible results of this work will be a comprehensive bistatic scattering database for use by radar system developers, along with a bistatic radar image simulator. Coupled with the clutter database, the simulator can be used to generate radar images of complex target scenes that can in turn be used for testing the performance of detection features developed for a specific system/application without having to build the system and image a scene.



Indoor hemispherical measurement of rough soil surface.

PROJECT LEADER

Prof. Fawwaz Ulaby, University of Michigan

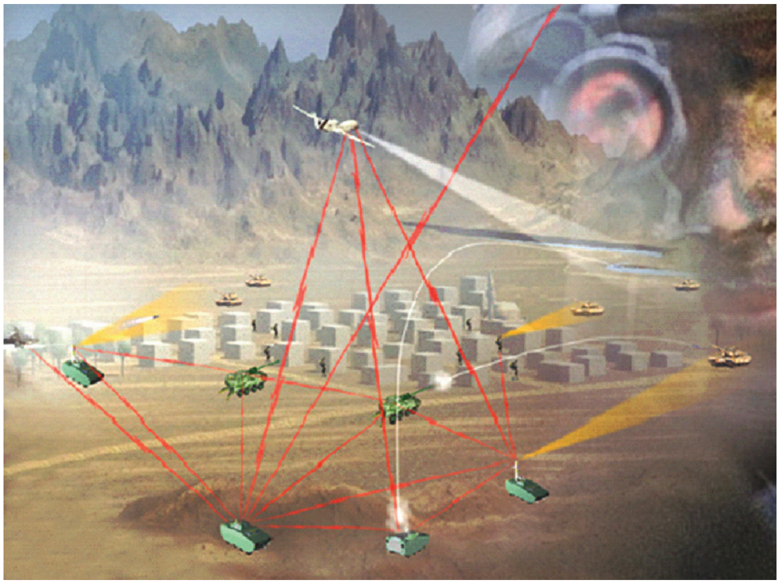
ADVANCED SENSORS

DECENTRALIZED DATA FUSION FOR MULTI-SENSOR, MULTI-MODE, MULTI-TARGET DETECTION, CLASSIFICATION AND TRACKING

DESCRIPTION

Networked fusion of orthogonal sensor data and information can provide unprecedented situational awareness for our Soldiers. Open fusion architectures that can support existing or envisioned tactical systems will enable superior situational awareness to be generated at the lowest echelons while being shared with command and control across the joint mission. Our research on Decentralized Data Fusion (DDF) has focused on developing a computationally efficient and accurate method of fusing and correlating sensor data within a limited communications bandwidth.

DDF is based on the construct of a network of sensor nodes, each with its own processing capability, which together do not require any central fusion or central communication facility. In such a system, fusion occurs locally at each node, based upon local observations and the information communicated from neighboring nodes. DDF provides a real-time spatial Common Operating Picture (COP) to all nodes in the network and because it is a decentralized system, it is scalable, modular and robust to single point of failure.



Future Combat Systems will fuse information across the network to gain situational awareness superiority.

Existing systems can benefit from open architectures that enable fusion of typically stove-piped sensor systems.

ACCOMPLISHMENTS

Created a unified data fusion architecture that provides efficient and accurate estimation and fusion of non-linear and non-Gaussian distributions for tracking and classification; effective scalability relative to growth in number of sensors, targets and region of coverage, and full decentralization.

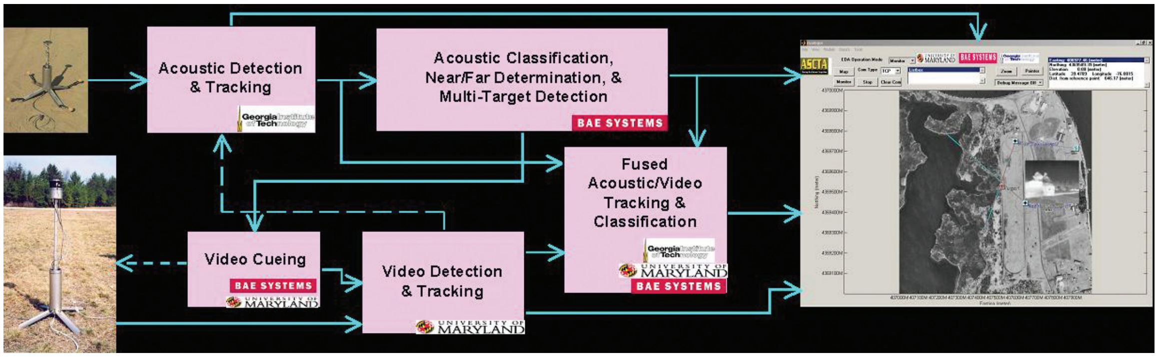
Incorporated extensions for Autonomous Sensor Management to include balancing of sensor observations to improve performance (i.e. detection, tracking, etc), balance performance vs. available sensor power usage, cross-cueing of sensors and control of mobile platforms.

Investigated the utility of particle filters in a decentralized system. Results lead to use of Generalized Lambda Distributions that will enable DDF network to operate with a wide range of sensor outputs (features).

Developed an extension that allows bearing only sensors (e.g. acoustic and imaging) to contribute to the decentralized network fusion.

Explored the communications energy consumption of DDF and related fusion architectures for unattended ground sensor networks.

Developed an approach called cluster-based fusion with feedback for communications that combines the



An example of integrated multi-vehicle tracking and classification using the fusion of acoustic and video data.

features of a linked cluster network topology with DDF algorithms for both fully connected and tree connected cases.

Developed a MATLAB simulation of collaborating robotic vehicles using DDF to implement a simultaneous localization and mapping capability and target tracking in non-flat terrain.

Collaborating with ARL researchers on experiments that will help to verify the fusion capability, reliability and scalability claims of DDF.

Demonstrated an integrated node-level fusion of multi-vehicle classification algorithms with acoustic and image processing.

PROJECT LEADERS

Mark Falco, BAE Systems

Dr. Mike Richman, BAE Systems

Dr. Geoff Edelson, BAE Systems

Dr. Dan Dudgeon, BAE Systems

Dr. Tien Pham, ARL

Dr. Raju Darmarla, ARL

Decentralized Data Fusion enables each unmanned platform to make local decisions to meet mission needs.

ADVANCED SENSORS

DESIGN METHODS FOR MICROSENSORS

DESCRIPTION

The Advanced Sensors Collaborative Technology Alliance has been developing tools for the automated generation of efficient embedded software from high level algorithm specifications. These tools employ power and performance optimization techniques to enable the use of low cost and highly flexible software over the employment of expensive and highly specific custom hardware with minimal impact to system performance. The ability to create designs that afford similar performance at a fraction of the cost results in significantly reduced acquisition costs and makes force multipliers like ubiquitous disposable sensors possible.

Our work on prototyping and experimentation with leveraging these synthesis techniques will lead to a better understanding of the limits of algorithm complexity that can be realized with low power, low cost, embedded processor technology. Distinguishing aspects of our approach compared to other low power approaches are the exploitation of novel, high-level models of computation, incorporation of integrated transformations to exploit heterogeneous modes of parallelism and memory management, and the demonstrated application of these ideas to low cost, ultra low power microcontrollers for disposable sensors.

Size, weight and cost are driving needed sensing capabilities at the small unit level.

In this work, we continue to apply the high-level programming techniques and software infrastructure that we are developing to our ongoing work on the dataflow interchange format Dataflow Interchange Format (DIF). This work will provide a valuable, common framework for developing an integrated, automated toolset for sensor network software implementation and new techniques for formally integrating design flow considerations of sensor network software with the dataflow paradigm. The framework's commonality affords users the ability to apply the developed design technology, experiment with extensions to the technology, and incorporate the technology into their own, possibly proprietary, tool chains.

Energy for signal processing is limited on many emerging robotic applications.

ACCOMPLISHMENTS

- Developed the DIF language and the associated Java package that provides dataflow-based representations and algorithm implementations for specifying and working with embedded applications across the evolving family of dataflow-based design tools.

- Developed new programming language constructs in the DIF for effectively capturing the structure of sensor node processing. These language constructs will enable efficient analysis and optimization of hardware/software structures for embedded processing of sensor signals.

Design tools can be applied to a wide range of autonomous or Soldier borne signal processing applications where size, weight and power are critical.

- Developed associated intermediate representations that enable language constructs to be exploited for software analysis, implementation, and optimization.

- Developed a new system synthesis technique that systematically cuts an application graph into subgraphs and allocates the subgraphs onto clusters in a hierarchically clustered sensor network. This enables efficient refinement of synthesized software for low power consumption.

- Experimented with synthesized software, refinement of low power synthesis techniques, and demonstration on microcontroller platforms.

PROJECT LEADERS

Dr. S. S. Bhattacharyya, University of Maryland

K. J. Ray Liu, University of Maryland

Rapid development of modular payloads enables Warfighters to have the right sensors at the right time.

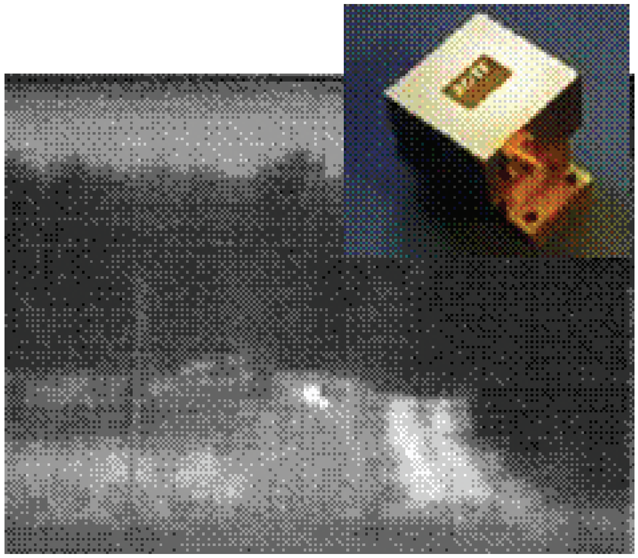
ADVANCED SENSORS

ENABLING TECHNOLOGIES FOR HYPERSPECTRAL IMAGING

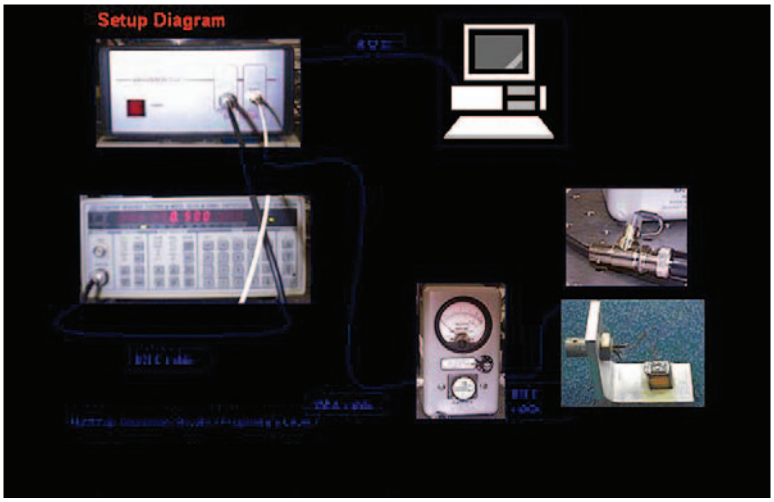
DESCRIPTION

The growing reliance on Intelligence, Surveillance, and Reconnaissance (ISR) assets for broad area target detection and identification, as well as specialized requirements in biochem detection and foliage penetration have increased the need for low cost, agile hyperspectral imaging systems. Today's asymmetric battlefield requires U.S. forces to possess the capability to detect and survive an initial Bio-Chem attack. To achieve this goal, the Office of the Secretary of Defense (OSD) anticipates an integrated suite of chemical and biological sensors.

The hyperspectral imaging camera will significantly enhance the performance of this suite of sensors by either taking the spectral signatures of the chemicals/hard targets present on the battlefield or by an active probe such as a laser, reducing interfering background signals by narrowing the spectral region being imaged. Our ASCTA vision has focused our research efforts on developing new Acousto-Optic Tunable Filter (AOTF) mercurous bromide crystals for next generation hyperspectral systems, to improve clutter suppression in infrared images and to develop components that enable spectroscopic systems for bio-chem detection.



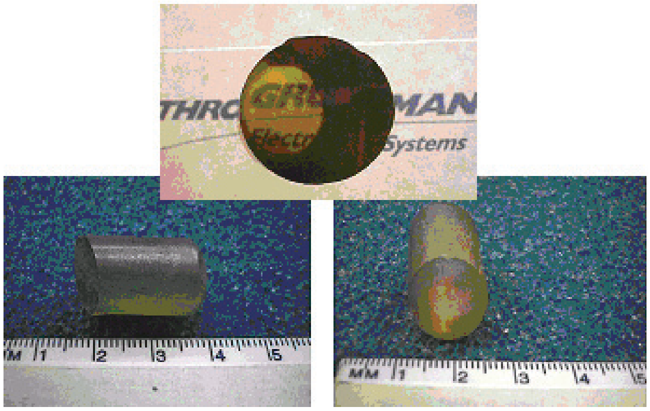
Hyperspectral image at 660nm revealing a truck concealed by a camouflage net. Insert shows an AOTF cell.



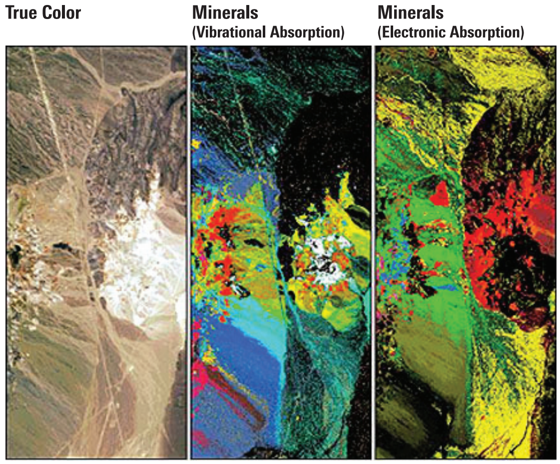
Hyperspectral imaging system and demonstration system components.

AOTFs are excellent sensors for passive detection of military objects of interest, such as chemical warfare agents and/or military vehicles in high clutter. The advantages of AOTFs include ruggedness (all solid state), versatility (computer controlled), covertness (passive operation), sensitivity (variable bandwidths and spectral derivatives), agility (quickly tuned to any wavelength), selectivity (accurately tunable to any spectral characteristic of the target), efficiency (high optical throughput), and easy interpretation (entire images).

Mercurous bromide is an excellent choice for AOTFs because it has a large transparency range (0.4 to 30 microns), a high Acousto-Optic (AO) figure of merit (2800 times better than quartz) needed for high efficiency and is easily designed to have the near optimum resolution for the detection of chemical warfare agents. Mercurous bromide AOTFs will lead to the development of a Real-Time Spectro Polarimetric Imaging (RTSPI) system operating in the 0.3-18 micron region of the spectrum enabled by mercurous bromide. The RTSPI makes use of discriminates based not only on shape and temporal properties but also on spectral content and polarization.



Design, fabrication for cm size mercurous bromide crystal and electrode was developed.



NASA image showing the remarkable use of hyperspectral imaging.

ACCOMPLISHMENTS

- First prototype AOTF hyperspectral imaging system demonstrated.

- First ever one cm size mercurous bromide high quality crystal grown. Mercurous bromide crystals have a transmission range from visible to 30-micron wavelength range and can make possible hyperspectral imaging to defeat clutter and camouflage.

PROJECT LEADERS

N.B. Singh, Northrop Grumman

A. Berghmans, Northrop Grumman

Infrared images will be improved by AOTF hyperspectral imager due to clutter suppression.

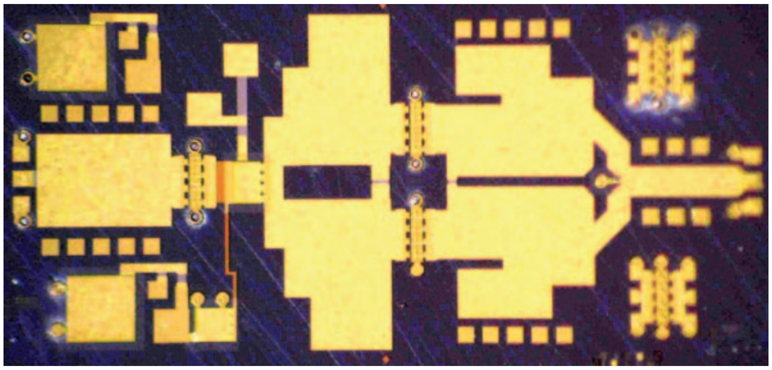
ADVANCED SENSORS

GALLIUM NITRIDE TECHNOLOGY FOR HIGH POWER, ROBUST MILLIMETER WAVE TRANSMITTERS AND RECEIVERS

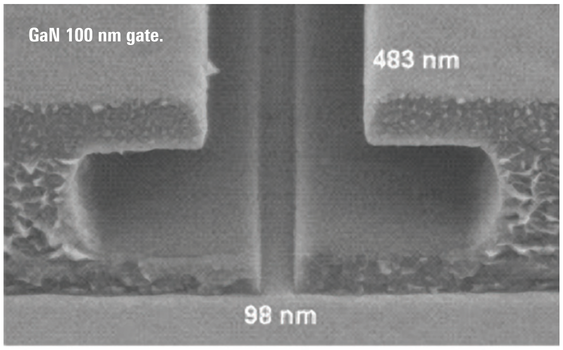
DESCRIPTION

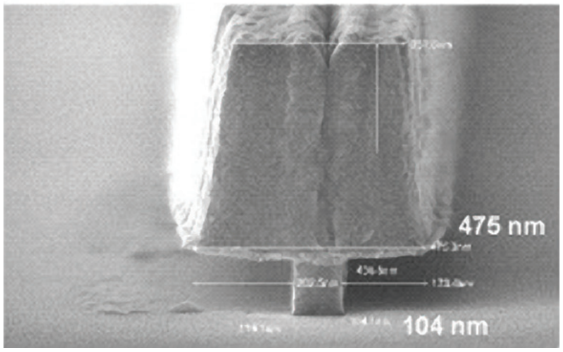
Gallium nitride (GaN) can sustain very high electric fields with respect to nearly all other semiconductor materials. While there is considerable interest in GaN for wireless infrastructure, development of GaN for millimeter wave applications has not progressed as rapidly. A significant demand exists for high power solid-state amplifiers at K_a- and Q-band for satellite and secure communications, as well as K_a-band missile, phased-array-radar, and multi-function RF system applications. GaN High Electron Mobility Transistors (HEMT) exhibit power densities10x higher than any other solid state device and are attractive because they provide a replacement for expensive and bulky traveling wave tube amplifiers used in present systems.

GaN offers a unique solution for extraction of information from extremely dense signal environments in the electronic battlefield of our current and future forces. In addition to jamming, friendly signals have the potential to create spurious signals and desensitize or even damage receivers. Traditional means to protect front-end electronics include use of limiters and large periphery devices, approaches that degrade noise figure and require additional power. GaN HEMTs will enable high-dynamic-range, robust receivers without sacrificing noise figure or DC power. These devices can be used without front end limiters, further improving system noise figure.



Small signal gain of 100 nm-gate GaN HEMT exhibiting figures of merit ft of 125 GHz and fmax of 174 GHz.



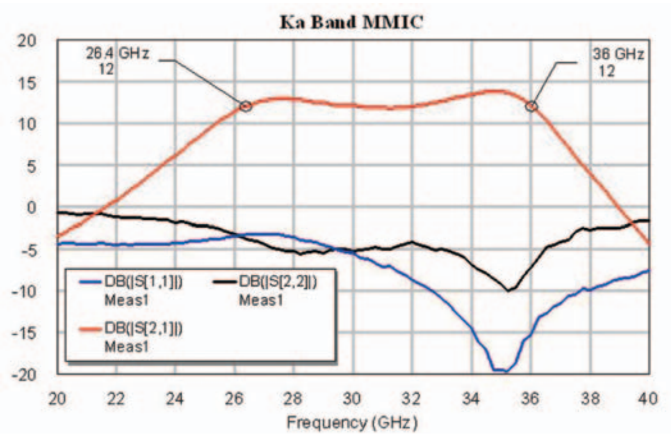


This program combined the collaborative expertise of four institutions to exploit GaN for mm-wave high power amplifiers and robust low noise amplifiers through fundamental material studies, process development, microwave monolithic integrated circuit (MMIC) design and fabrication.

- Cornell: Understanding factors limiting electron velocity in AlGaN/GaN, and optimizing high electron mobility transistor (HEMT) designs for high gain and power density.
- ARL: Design of high power K_a-band MMIC amplifiers.
- Rockwell Science Center: Process development and fabrication of power MMICs radar cross section.
- BAE Systems: Development and fabrication of low noise and power HEMTs.

ACCOMPLISHMENTS

- Means of improving average electron transit velocity to more than 1.5e7 cm/s, have been devised through enhanced electron confinement, using a thin (1.5 nm)



K_a-band 5 watt GaN power amplifier MMIC.

PROJECT LEADERS

P.C. Chao, BAE Systems

Anthony Immorlica Jr., BAE Systems

Karim Boutros, Rockwell Science Center

Lester Eastman, Cornell University

Ali Darwish, ARL

Alfred Hung, ARL

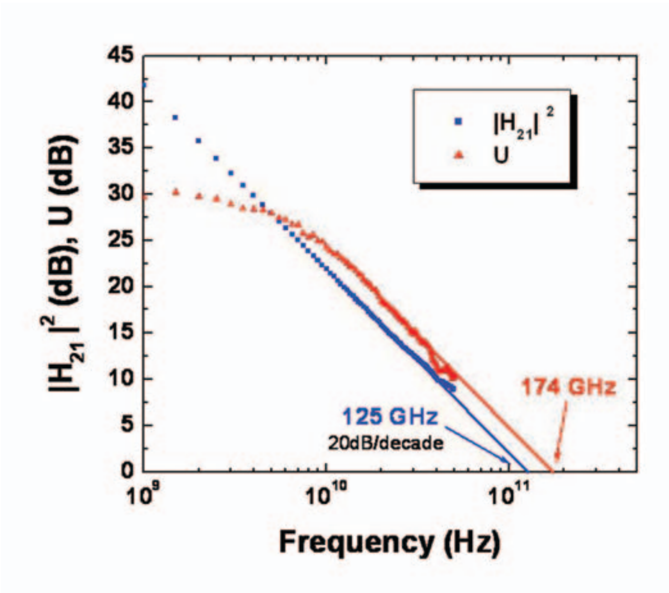
Ed Viveiros, ARL

Michael Wraback, ARL

aluminum nitride barrier above, and a 4 nm indium gallium nitride barrier below the GaN channel. Other novel structures have been designed for increasing device gain, including doped and graded channel heterostructures.

- Our demonstration of 4.5 W/mm at 40 GHz is ~10X higher power density than GaAs pseudomorphic HEMTs, and represents the highest power density from any solid-state device at this frequency. These record results prove the suitability of GaN for use in K_a- and Q-band high-power MMICs.

- Low noise, 100 nm-gate GaN HEMTs have been fabricated, exhibiting a state-of-the-art noise measure of 1.4dB at 30GHz. This is equivalent to what is achieved by today's gallium arsenide and indium phosphide based technologies, but with greatly enhanced robustness and linearity.



S-parameters of a wideband K_a band MMIC exhibiting 13 dB linear gain over a 10 GHz bandwidth.

ADVANCED SENSORS

HOT FOCAL PLANE ARRAYS ENABLING HIGH RELIABILITY, REDUCED LIFECYCLE COST PASSIVE IMAGING SYSTEMS

DESCRIPTION

Higher operating temperature focal plane arrays (FPAs) is a persistent Army objective established to reduce the total cost of ownership and increase long term reliability of long range passive imaging systems. The primary focus of our ASCTA work is to develop the enabling technologies for: (1) lower cost imaging systems to afford wider proliferation of 3rd generation forward looking infrared (FLIR) technology, (2) reduced imaging system weight increasing mobility and shortening logistic tail, and (3) extended system lifetime and higher reliability minimizing system lifecycle cost.

The Higher Operating Temperature (HOT) focal plane passive imaging effort is focused on maturing growth processes, modeling materials and prototype array fabrication. ASCTA is working on two HOT passive imaging approaches to achieve 120K operating temperatures in large format mid wave/long wave FLIRs and achieving these goals: (1) The more established Mercury Cadmium Telluride (MCT) material system, and (2) a relatively immature but very promising III-V materials technology in which the staggered (type II) band lineup of a gallium antimonide/indium arsenide (GaSb/InAs) Strain Layer Superlattice (SLS) is exploited to yield long cut-off wavelength.

The MCT effort is a joint endeavor between the University of Illinois-Chicago, DRS Technologies and ARL with an established objective of producing highly pure MCT with low background doping below 1e15 cm^{-3}. The second goal of this research is to extrinsically dope molecular beam epitaxy (MBE) grown MCT which will lead to an increase in the operating temperature of long-wavelength infrared (LWIR) MCT photon detector imaging arrays.

We are developing the enabling technologies required to produce large format HOT detectors for long range target acquisition, detection, and targeting.

HOT detector FPAs will allow the Soldier to carry a longer life lighter weight imaging, system allowing greater mobility.

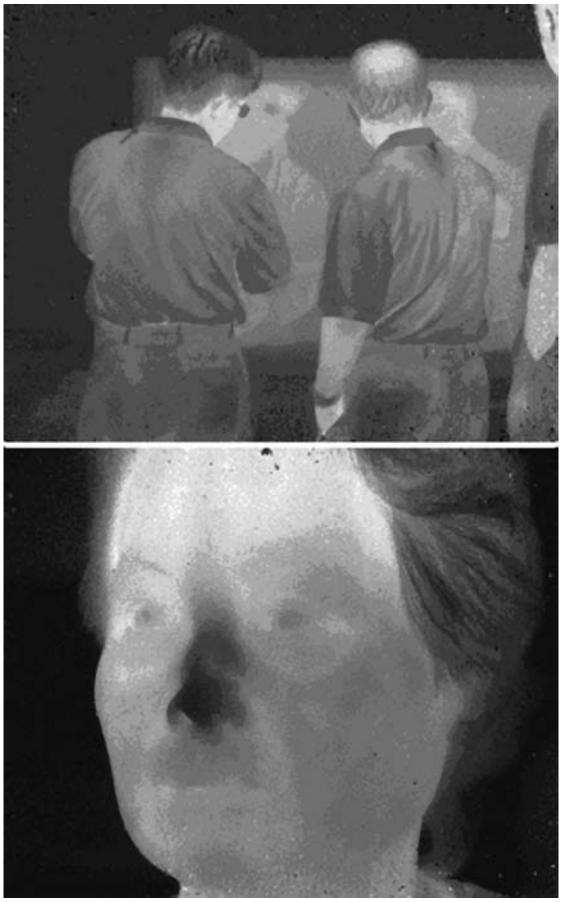
The SLS arrays project is a joint endeavor between the University of New Mexico, BAE Systems, and ARL focused on developing high structural and electrical quality MBE growth of GaSb/InAs materials. This research promises to afford midwave infrared (MWIR) arrays operating at 180K and LWIR arrays operating at 120K.

ACCOMPLISHMENTS

A novel P+n-n+ MWIR MCT structure was used to demonstrate the best ever R_0A of 5e8 ohm-cm^2 with a peak dynamic impedance of 1e9 ohm-cm^2. An operating temperature of 200K was demonstrated.

Demonstrated the first U.S. developed 256 x 256 MWIR focal plane array. Currently on track to demonstrate an LWIR focal plane array.

Demonstrated MWIR MCT arrays, with higher than 120K operating temperature.



First in the U.S. and second in the world 256 x 256 SLS camera. These images are from a MWIR SLS detector array on a commercial readout circuit.

PROJECT LEADERS

Dr. Parvez N. Uppal, BAE Systems

Michael Winn, BAE Systems

Dr. John Little, ARL

Dr. Stefan Svensson, ARL

Demonstrated MWIR SLS arrays with 100K operating temperature.

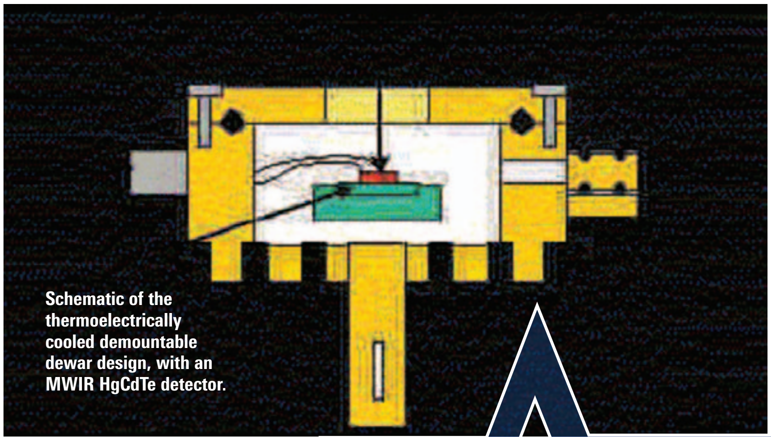
Achieved operating temperature of 200K demonstrated in HgCdTe MWIR array.

SLS material growth parameters were optimized.

Demonstrated good single pixel MWIR SLS device with background limited performance up to 200K.

MCT extrinsic doping studies.

Device process developed for SLS.



Schematic of the thermoelectrically cooled demountable dewar design, with an MWIR HgCdTe detector.

ADVANCED SENSORS

HUMAN GAIT DNA

DESCRIPTION

Use of multi-node sensors will enable persistent and enhanced detection, classification and tracking of occluded humans and vehicles over a wide area. The ability to conduct real-time activity analysis and anomaly detection will serve as an invaluable tool in security and insurgent identification applications ranging from improvised explosive device (IED) emplacement detection to airport security to suicide bomber early warning. We have developed a compact signature for characterizing human gait and a set of activities corresponding to humans carrying objects such as a back pack, handbag or briefcase.

Our approach is based on analyzing surfaces in space and time, which form graph results in a twisted helical pattern resembling human DNA and "Human Gait DNA." It is shown that the patterns sufficiently characterize human gait and activities. The advantages of Double Helical Signature (DHS) are: (1) it naturally codes appearance and articulations; (2) it reveals an inherent geometric symmetry (FriezeGroup), and (3) it is effective for representing gait and activities.

Human gait processing and persistent surveillance might be used to detect humans carrying and burying items of interest.

Providing sensors with automated processing will enable Warfighters to focus on the mission, not the sensors.

Geometric group theory serves as the basis for the formulation of our work. To simultaneously learn and extract the structure of DHS, an iterative local curve embedding algorithm is applied and the geometric constraints that are useful in matching DHS across different viewing directions and individuals are exploited.

ACCOMPLISHMENTS

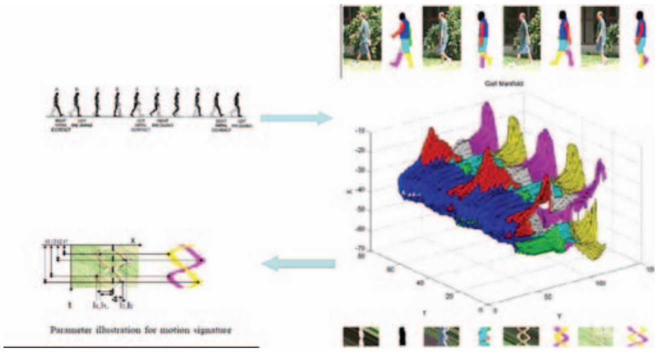
- Successfully integrated the Human Gait DNA into a real-time surveillance system capable of localizing pedestrians without requiring landmarks. The system is robust to target size, moving direction, shadows and occlusions. Our system can match spatial-temporal signatures generated by human motion in different views and time instants and is effective for classifying activities such as carrying objects (visible and concealed). In addition, our approach affords the real-time identification of "dropped" objects, provides for accurate height estimation of personnel, and is robust in crowds. By recognizing various symmetries, we provide a robust solution that does not depend on silhouettes and landmarks. Extensive experiments indicate that the approach is superior to many existing methods in terms of accuracy and reliability.

PROJECT LEADERS

Dr. Rama Chellappa, University of Maryland

Dr. Volkan Cevher, University of Maryland

Dr. Yang Ran, University of Maryland

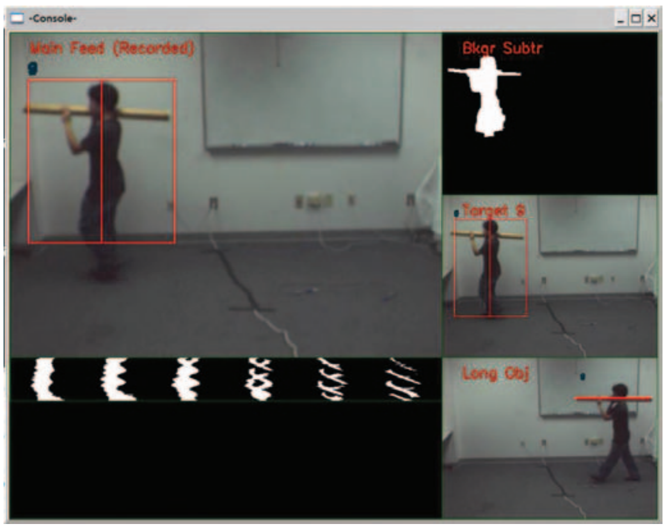


Features extracted from video of human gait produce double helix data structures that resemble DNA strands.

- Developed behavior-based tracking algorithms for detecting abnormal human movements in a crowd.
- Implemented a pedestrian monitoring system capable of simultaneously segmenting and labeling body parts, matching across various cameras and time as well as recognizing load carrying events.
- Demonstrated the effectiveness under lighting changes, shadows, camera motion, various viewing angles as well as severe occlusions.

Sensitivity analysis shows the robustness for several key factors such as body movement direction, viewing angle, and target size.

This work indicates that considering human motion in spatial-temporal domain is a highly efficient method to analyze gait and monitor activities.



Processing of DNA data structures can be used to detect anomalous behavior (e.g. carrying, dropping objects). In this example, a person is holding a tube horizontally on his shoulder.

ADVANCED SENSORS

MICRORADAR FOR PERSONNEL DETECTION IN REMOTE AREAS

DESCRIPTION

Sensors can aid Soldiers in accomplishing border patrol and perimeter defense missions in remote areas by providing reliable, persistent surveillance. RF microsensors can provide unique personnel and vehicle detection capabilities such as the ability to detect and track targets and classify humans based on features of human motion (gait) in all-weather/illumination conditions. Additionally, microradar produces target features such as velocity and range to target which are complimentary to features of other micro sensor modalities and can be fused to enhance networked sensor performance. Existing small-size and low-power RF sensors are limited to short range. The emphasis of our work has been to extend the detection range of both vehicles and personnel, while maintaining reasonable size and power constraints.

Microradar supports surveillance missions where all weather/illumination conditions are required.

ACCOMPLISHMENTS

A small, low-power, frequency modulation continuous wave (FMCW) range/velocity microradar for remote application has been designed and implemented to measure the range and velocity of multiple targets. The capabilities of the RF microsensor to detect and track both vehicle and human targets at ranges of more than 100 meters have been demonstrated. This sensor incorporates a digital signal processor to provide range, velocity and target amplitude (size) information. Since it has been designed to detect targets at all ranges less than maximum detection range, it can be considered an "all range" sensor, as contrasted to a tripwire sensor that detects targets at a single range. Data from the RF sensor has been used, with unique human-gait algorithms, to measure high-resolution Doppler features of walking human targets for personnel classification (with promising discrimination to animals).

Remote, reliable and persistent surveillance reduces burden on Soldiers.

- Several systems have been prototyped for transition to McQ Associates for use in their deployed system OmniSense.
- Over 200 hours of tests with current design. Tests have indicated good detection and tracking of vehicles and humans in near-operational environment.
- Multiple-target detection of humans beyond 200 meters and large vehicles beyond 400 meters.
- New algorithm improvements focused on tracking and statistical classification to separate and classify human and vehicle targets have been implemented and tested.
- Testing with a new spectral width feature has shown encouraging results. More training and testing of actual targets is underway.

FMCW microradar, approximately 4 X 6 X 2.4 inches in size running on 225 mA @ 12V provides range, velocity, relative size, classification and confidence level for three classes (human, vehicle, other).

PROJECT LEADERS

James Kurtz, University of Florida

Thyagaraju Damarla, ARL

- A new communication structure has been developed for the radar microsensor that will support anticipated future data formats and controls. Data outputs will include target class and probability of classification for sensor fusion applications.
- An approach for fused RF sensor and video (image) processing has been developed for future applications.
- The detection and tracking signal processing techniques for radar have been transitioned to an Army Small Business Technology Transfer (STTR) program called Remote Detection of Riverine Traffic.

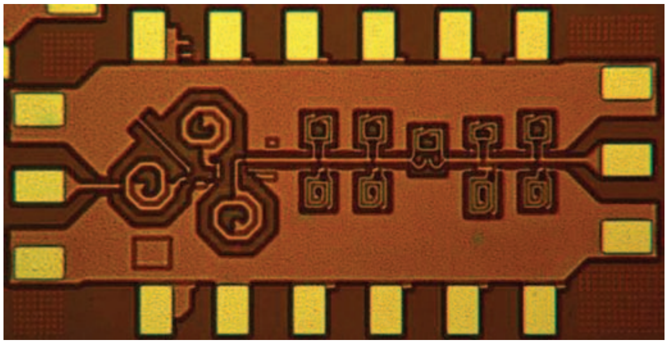
Microradar technology is maturing for near-term deployment in Army applications.

ADVANCED SENSORS

MULTIFUNCTION RF DEVICES–ENABLING AFFORDABLE MILLIMETER-WAVE ELECTRONICALLY SCANNED ARRAYS

DESCRIPTION

Electronically scanned arrays offer revolutionary capabilities for military platforms – combining radar, command and control and satellite communications on-the-move in a single, low profile antenna. However, wide deployment of electronically scanned arrays (ESAs) has unfortunately been limited by the high cost of III-V semiconductor devices which have until now been required to achieve acceptable performance at millimeter wave frequencies. While much lower cost silicon germanium (SiGe) integrated circuits have shown remarkable results for digital applications, the technology has not yet been exploited for millimeter-wave analog applications.



A SiGe K_a-band low noise amplifier integrated with a CMOS 4-bit phase shifter built in the IBM 8HP process.

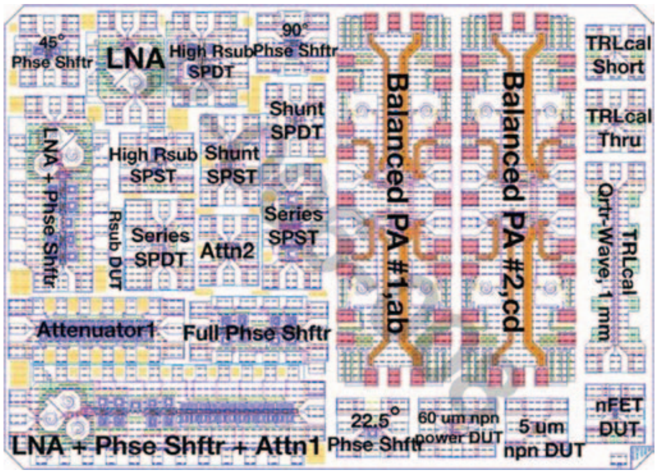
The advantages of SiGe are many:

1) Because it is based on a silicon platform, Complementary Metal Oxide Semiconductor (SiGe/CMOS) is very low cost.

2) Because SiGe is conveniently combined with CMOS, it facilitates integration of necessary analog and digital functions such as shift registers, control and calibration electronics, digital phase shifters and attenuators, and amplifiers on a single chip which is difficult to realize with GaAs.

3) Because it is a mature technology, SiGe/CMOS has very high yields allowing cost effective integration of several analog functions on the same chip. This will allow each element in the phased-array to be much more compact compared to GaAs solutions.

4) Finally, it is conceivable to fabricate several transmit/receive elements on a single chip, greatly simplifying the construction of an ESA, resulting in additional cost savings.



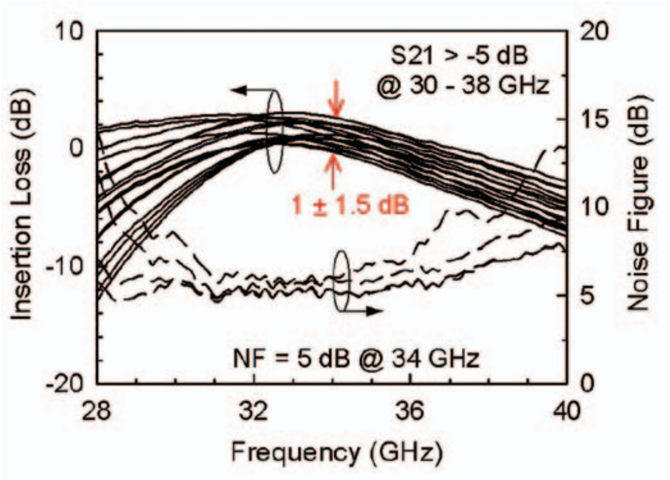
35 GHz MMIC chip set designed for the IBM 8HP SiGe/CMOS Process.

This project is aimed at pushing the limits of Si-Ge technology through the design and test of analog and mixed signal K_a-Band circuits for transmit/receive modules. Individual circuit building blocks are being designed and fabricated in the IBM HP8 process and will eventually be integrated into a single chip on a path to our eventual vision of a wafer scale phased array system.

ACCOMPLISHMENTS

Under this program, a number of K_a-Band building block Monolithic Microwave Integrated Circuits (MMICs) have been designed, fabricated and tested. These include:

- A state-of-the-art SiGe power amplifier with more than 100 mW of RF power at 32-33 GHz and 10 percent power added efficiency. The amplifier also delivered more than 50 mW of RF Power from 26-40 GHz and has shown the best performance to date of any SiGe or CMOS chip at mm-wave frequencies.



Measured gain and noise figure of the K_a-band LNA.

PROJECT LEADERS

Gabriel M. Rebeiz, University of Michigan/
University of California

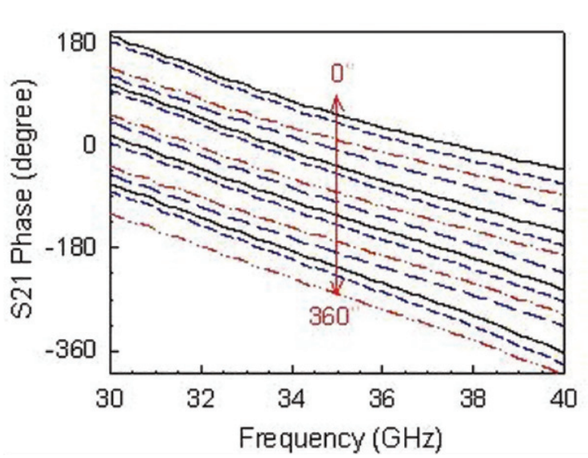
Alfred Hung, ARL

Ed Viveiros, ARL

Eric Adler, ARL

- A SiGe low noise amplifier with 3 dB noise figure.
- Extremely small (less than 0.3 mm^2) 4-bit phase shifters and 3-bit variable attenuators.
- Very high isolation switches covering 26-40 GHz with 1.5 dB loss and greater than 30 dB isolation.

As additional circuit functions are designed and implemented, integration of these and other key components onto multiple transmitter/receiver modules on a chip will result in a breakthrough in the cost of ESAs, leading to wide deployment as an organic asset.



Measured phase shift of the K_a-Band chip.

COMMUNICATIONS AND NETWORKS

COMMUNICATIONS AND NETWORKS

COMMUNICATIONS AND NETWORKS CTA OVERVIEW

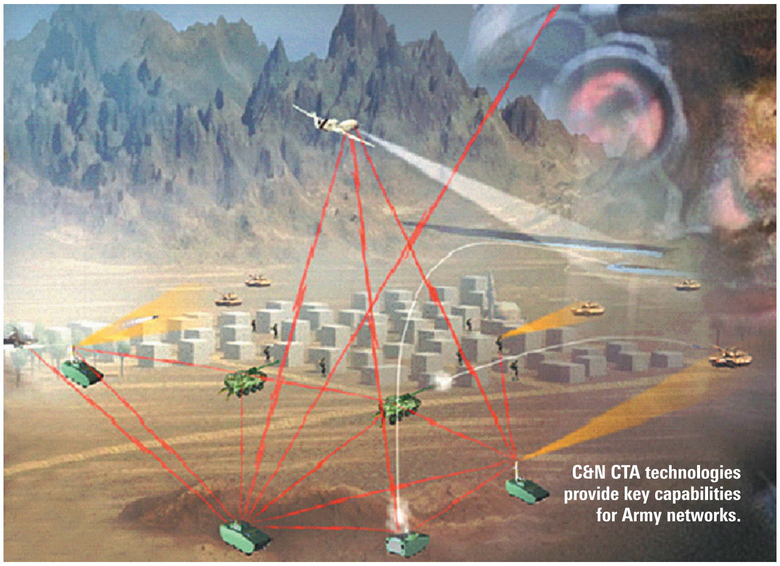
OBJECTIVES

The Future Force will exploit and depend on mobile, adaptable, and secure communication networks to enhance its survivability and lethality. Available communications bandwidth must be used efficiently, and information must be disseminated rapidly, so that the right information is available to Warfighters at the right place and time. Army networks must interoperate with joint, combined, and multinational forces to meet the wide range of missions envisioned for the Army of the future.

The Communications and Networks CTA (C&N CTA) aims to develop technologies that are the foundation for large, heterogeneous, wireless communication networks. Our technologies will enable:

- High data rate wireless communications that are hard for the enemy to detect or intercept.
- Protocols that enable the network to be very dynamic and unpredictable, with all elements of the network moving.
- Protocols that automatically configures on-the-fly so that mobile networks can be quickly and flexibly deployed.
- Efficient security services that protect the wireless mobile ad hoc networks (MANETs) without reliance on strategic services.

In parallel with the research program, we actively seek opportunities to transition the fruits of this research to programs that are paving the path for the Army's vision of network-centric warfare.



C&N CTA technologies provide key capabilities for Army networks.

C&N CTA partners and individual contributors.

TECHNICAL AREAS

The C&N CTA conducts research in the following Technical Areas:

- Survivable Wireless Mobile Networks develops the networking capabilities to enable the Army's Vision of information dominance. We develop technologies to ensure that tactical networks are self-configuring and self-maintaining, highly mobile, survivable, scalable, energy-efficient, and interoperable with joint and coalition forces.
- Signal Processing for Secure Communications and Networking provides the signal processing foundation for advanced tactical communications for on-the-move ad hoc networks in environments ranging from dense urban cores to high-foliage wooded settings. Our technologies ensure network survivability under hostile mobile conditions on the move, under severe bandwidth and energy constraints, avoiding detection, being aware of the environment, and providing robustness to jamming.
- Tactical Information Protection develops technologies in two key areas. We develop essential security services and infrastructure needed to prevent attacks, while accommodating self-configuring, dynamic networks; limited bandwidth; noisy, unreliable communications; and limited energy. We develop capabilities to accurately and quickly detect and identify vulnerabilities and attacks using tools and techniques that are automated, scalable, efficient, adaptive, and secure.

There is a strong inter-relationship among the Technical Areas of the research conducted so as to capitalize on opportunities to achieve improved performance via cross-layer design.

C&N CTA technologies will enhance Soldiers' situational awareness through enhanced networks.

ACCOMPLISHMENTS

- The Multi-Objective Network Optimization and Assessment Tool (MONOPATI) provides automated generation of optimal network hierarchies that allow a large force to operate immediately upon arrival in a theater. This research has been transitioned to the Communications and Electronics Research, Development and Engineering Center (CERDEC) Network Design program.

- The Distributed Survivable Resource Control-Tactical (DSRC-T) framework improves core networking schemes by controlling and managing their resources. This research and a TRL-5 demonstrator have been transitioned to the CERDEC Proactive Integrated Link Selection for Network Robustness (PILSNER) program.

- Our Multiple-Input Multiple-Output (MIMO) technologies exploit the spatial dimension of radio communications, offering benefits previously not realizable using single antenna links. Experiments have demonstrated spectral efficiency exceeding 25 bps/Hz. This research has been transitioned to CERDEC classified programs.

- The C&N CTA has generated 13 technology transition task orders, with key transitions to CERDEC MOSAIC, PILSNER, TWNA, Network Design, I2WD programs, DARPA CN, XGEN programs, FCS LSI, FCS System Design and Development (Net Mgmt), TMOS, JTRS Cluster 5 and Navy Digital Modular Radio, and IETF and IEEE 802.16 standards.

- Other C&N CTA metrics include: 300+ journal and 500+ conference papers; 40 invention disclosures, 15 patent applications and 8 patents; 38 talks and 4 special workshops; 50 Doctoral and 22 Masters degrees awarded under CTA sponsorship; 33 staff rotations and student summer internships.

PARTNERS

The C&N CTA membership comprises the following five industry and nine university partners:

Telcordia Technologies, Piscataway, NJ (Lead Member)

BAE Systems, Wayne, NJ and Nashua, NH

BBN Technologies, Cambridge, MA

General Dynamics C4S, Scottsdale, AZ and Atlanta, GA

SPARTA Inc, Columbia, MD

City College of New York, New York, NY

Clark Atlanta University, Atlanta, GA

Georgia Institute of Technology, Atlanta, GA

Johns Hopkins University, Baltimore, MD and Laurel, MD

Morgan State University, Baltimore, MD

Princeton University, Princeton, NJ

University of Delaware, Newark, DE

University of Maryland, College Park, MD

University of Minnesota, Minneapolis, MN

The C&N CTA has augmented its core membership with specialized research from individual investigators at the following seven universities:

Cornell University, Ithaca, NY

University of Michigan, Ann Arbor, MI

University of Washington, Seattle, WA

Howard University, Washington, DC

New Mexico State University, Las Cruces, NM

University of California Riverside, Riverside, CA

University of California Davis, Davis, CA

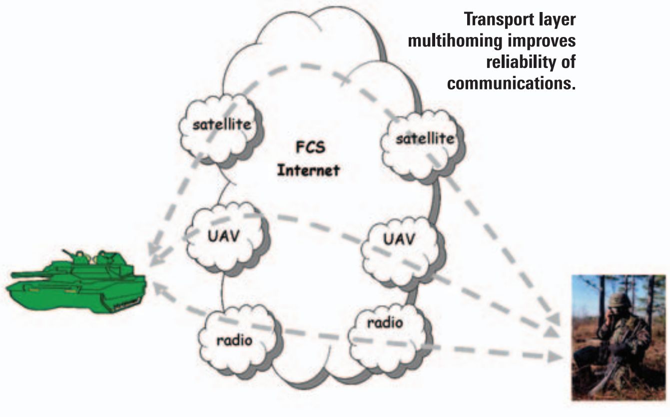
Communications and networks are critical to maintaining Soldier awareness and survivability.

COMMUNICATIONS AND NETWORKS

ASSURING PERSISTENT, FAILURE-FREE SESSION

DESCRIPTION

Transport and session layers provide the essential link between the application and network communication layers. These two layers are vital to supporting end-to-end reliability, security and quality-of-service. Tactical wireless communications and battlefield environments present daunting challenges that existing transport and session technologies cannot meet. Warfighters should never be concerned with restarting or reestablishing end-to-end sessions, both of which divert attention and resources from the more important tasks at hand. Our goal is to provide technologies that maintain uninterrupted connections for FCS applications in the presence of high node mobility and failure.

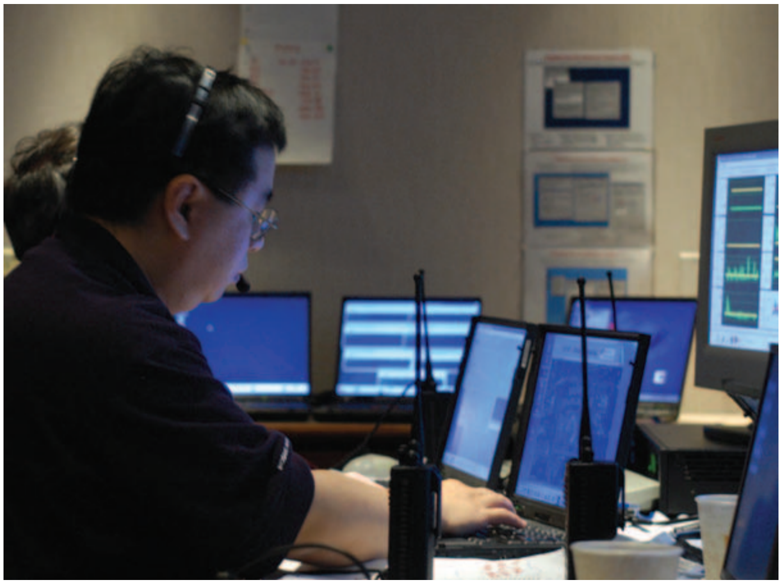


Transport layer multihoming improves reliability of communications.

ACCOMPLISHMENTS

Our key accomplishment has been to incorporate features benefiting Army network operation into the Stream Control Transmission Protocol (SCTP) Internet Engineering Task Force (IETF) RFC4460 draft standard. By virtue of standardization, the Army will have access to mutliple commercial off-the-shelf (COTS) products that meet the needs of the Future Force. Achieving this goal required extensive design, testing and evaluation:

- Concurrent Multipath Transfer (CMT) is a key technology we developed for supporting multiple transfer streams. To test and evaluate CMT, we incorporated it into the widely available FreeBSD SCTP implementation, and tested this using the University of Delaware's Protocol Engineering Laboratory's emulation test network. Furthermore, we integrated a CMT module into the widely used simulation tool ns-2, facilitating international SCTP simulation research. We also designed and implemented an Apache web server and a Firefox web browser that employed SCTP. This software is available for public download. Aside from validating our work, we generated software that the Army, other research institutes and universities can use and build upon.

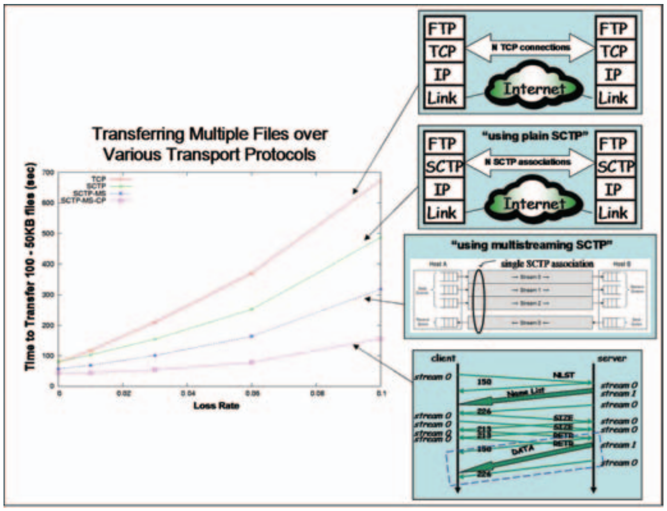


- Since it will be infeasible to re-engineer all Army applications to use SCTP, we designed and evaluated a transparent Transmission Control Protocol (TCP)-to-SCTP translation shim layer that allows legacy applications to enjoy the benefits of SCTP. We demonstrated that the shim works reliably for legacy TCP applications, and that applications using the shim perform equivalently or better than when run over TCP.

SIGNIFICANT PUBLICATIONS

J. Iyengar, P. Amer, R. Stewart. "Performance implications of a bounded receive buffer in concurrent multipath transfer," *Computer Communications* (in press).

J. Iyengar, P. Amer, R. Stewart. "Concurrent multipath transfer using SCTP multihoming over independent end-to-end paths," *IEEE/ACM Trans on Networking*, 14(5), 10/06.



SCTP shows clear improvements when transferring multiple files.

PROJECT LEADERS

Dr. Paul Amer, Dr. Gonzalo Arce, University of Delaware, Newark, DE

Dr. Mariusz Fecko, Sunil Samtani, Telcordia Technologies, Piscataway, NJ

Dr. Tarek Saadawi, Dr. Myung Lee, Dr. M. Ümit Uyar, City College of New York, New York, NY

Dr. Armand Makowski, Dr. Richard La, University of Maryland, College Park, MD

A. Caro, P. Amer, R. Stewart. "Retransmission policies for multihomed transport protocols," *Computer Communications*, 29(10), 6/06.

A. Caro, P. Amer, R. Stewart. "Rethinking end-to-end failover with transport layer multihoming," *Annals of Telecommunications*, 61(1-2), 1/06.

P. Natarajan, J .Iyengar, P. Amer, Stewart. "SCTP: An innovative transport layer protocol for the web,"*15th Int'l World Wide Web Conf, Edinburgh*, 5/06.

Ph.D. Dissertation: Janardhan Iyengar. "Concurrent multipath transfer using SCTP multihoming," *CIS Department; University of Deleware*, 2006.

Ph.D. Dissertation: Armand Caro. "End-to-end fault tolerance using transport multihoming," *CIS Department, University of Deleware*, 2005.

SCTP enables support for multiple concurrent communications with appropriate quality-of-service from a single communications terminal.

COMMUNICATIONS AND NETWORKS

AUTOMATIC NETWORK DOMAIN OPTIMIZATION

DESCRIPTION

Hierarchy and aggregation improves scalability, manageability and efficiency. Hierarchy configuration, however, has been either a manual process or based on simple heuristics. The manual process requires specialized skills, which are time consuming, prone to errors, and unadaptable to dynamically changing conditions. Simple heuristics do not account for factors such as network heterogeneity.

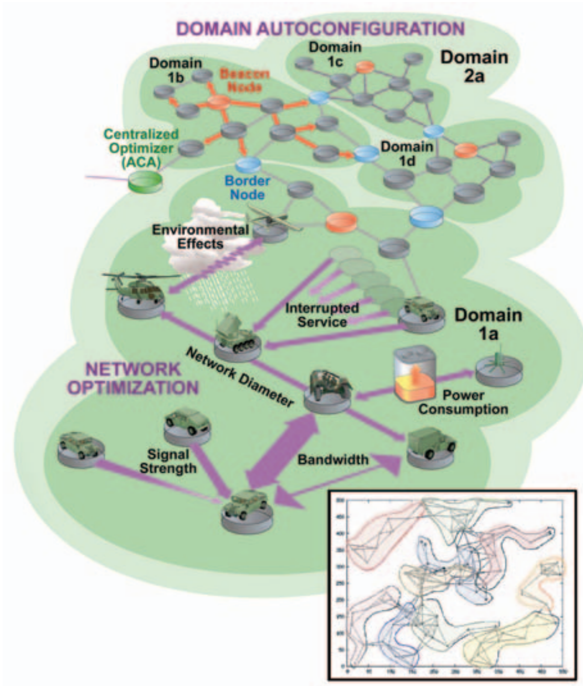
Our goal is to develop new automated techniques to generate optimal hierarchies that allow a large force to operate immediately upon arrival in a theater. The mechanisms must also rapidly and robustly adapt the hierarchies to changing environments. We have designed and implemented the MONOPATI that has three components:

- Hierarchy optimization uses enhanced Simulated Annealing with complex cost functions and constraints that decrease the convergence time by several orders of magnitude without significant loss in cluster optimality (typically less than 1 percent).

- Local maintenance uses distributed beacon protocol and neighbor dependent reassociation functions that are robust to network splits and merges and do not rely on fixed infrastructure.

- Heterogeneous configuration dynamically adjusts the protocols and elements of each domain to the particular requirements and environment.

Domain autoconfiguration is key to enabling survivable and scalable Army tactical networks.



Domain autoconfiguration in action.

Some of the applications of the MONOPATI tool are the formation and maintenance of domains:

- With specific physical characteristics.

- That are robust to topology changes.

- That improve routing (reduce overhead and hierarchical path stretch).

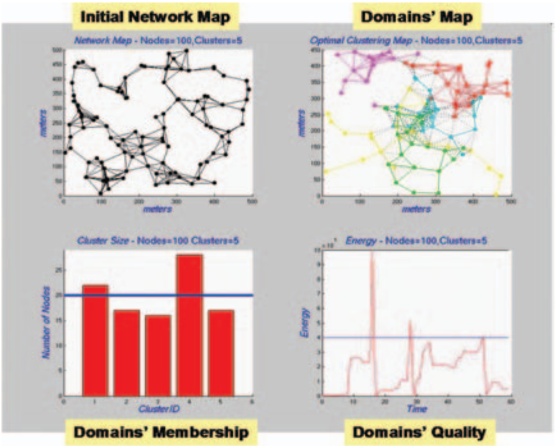
- That improve efficiency and resource utilization of Intrusion Detection.

ACCOMPLISHMENTS

The research accomplishments of this task focus on the design of MONOPATI and its individual functional components. The main research accomplishments are:

- We devised the mathematical formulation of objective functions and constraints representing and abstracting diverse and complex performance requirements.

- We enhanced our global stochastic approximation algorithm (Simulated Annealing) to optimize network structures according to specified objective functions and constraints.



Our technologies maintain domain size and energy usage in Army networks.

- We developed novel and versatile active distributed maintenance approaches for improving the survivability of the MONOPATI tool in highly dynamic environments. We were able to improve the efficiency of the various functional components that constitute the tool.

- MONOPATI is able to simultaneously improve multiple metrics by:

  - Reducing routing overhead by over 15x.

  - Reducing stretch (route sub-optimality) over 45 percent.

- MONOPATI provides a powerful optimization framework in that it:

  - Can analyze a 1000 node network in 19 seconds (prior techniques required 30 minutes).

  - Produces no significant loss in structure optimality.

- MONOPATI demonstrated dynamic reconfiguration of Linux routers:

  - Initially, AODV dropped 78 percent of the packets, but after MONOPATI reconfigured the unstable link area to flood, packet loss was reduced to 18 percent.

- The domain autoconfiguration work has been transitioned to several Army programs:

  - CERDEC MOSAIC ATD included domain autoconfiguration in its TRL-5 and TRL-6 demonstrations.

  - CERDEC Tactical Wireless Network Assurance (TWNA) employs autoconfigured domains to isolate intruders.

  - CERDEC Network Design Project employs MONOPATI as a key element in the design of an intelligent and automated network design manager.

PROJECT LEADERS

Dr. Kyriakos Manousakis, Dr. Anthony McAuley, Telcordia Technologies, Piscataway, NJ

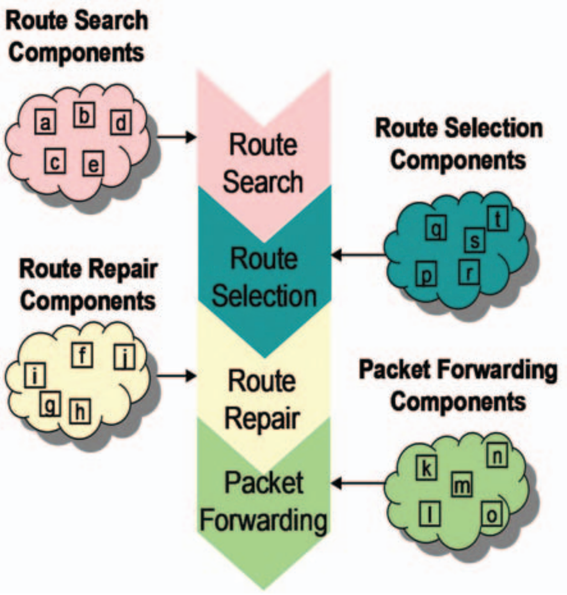
Dr. John S. Baras, University of Maryland, College Park, MD

Network optimization helps maintain Soldier communications in spite of physical obstacles and Soldier movement.

COMPONENT BASED ROUTING

DESCRIPTION

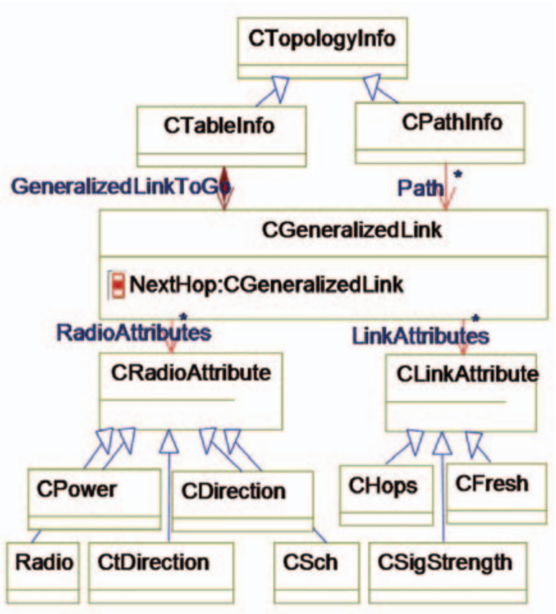
Research has clearly shown that routing protocols that perform well in some environments perform poorly when the environment and/or the performance metrics are changed. In order to achieve good performance in the diverse conditions and demands of future Army networks, the routing system must be capable of deploying different routing algorithms when conditions and needs change. To meet this objective, component-based routing (CBR) constructs routing protocols on-the-fly from routing components. There are three challenges facing component-based routing. First, a routing system must be designed to support the switching of components. Second, it must be determined when a particular version of a component should be used. For this second task, analytic models of routing component performance will be developed. The third task focuses on techniques and algorithms that sense the environment and determine which instances of each component should be used.



Component-Based Routing. The routing system is divided into basic components. A particular protocol is constructed from different versions of each component.

ACCOMPLISHMENTS

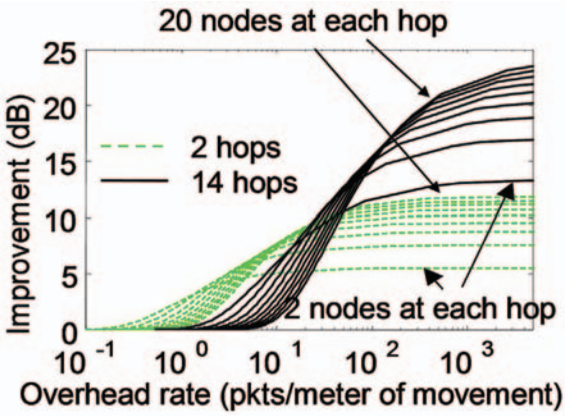
The CBR accomplishments are divided into three categories: (1) the design of the CBR system that supports component switching; (2) the understanding and modeling of the fundamental performance trade-offs facing routing, and (3) the development of new environment-aware routing algorithms.



Unified Modeling Language (UML) description of topology information in Component-Based Routing system.

(1) Designing the CBR system: Routing protocols are traditionally composed of elements that are tightly interwoven, and hence a change in one component requires changes in several other areas. However, our CBR system design has demonstrated that the routing protocols can be componentized in such a way that new routing protocols can be developed by combining the components in different ways. The key features of the CBR system are:

- Routing algorithms that can be categorized as a set of particular versions of components.
- New and existing protocols that can be generated by selecting particular versions of each component.
- Executable Universal Modeling Language (UML) representations of the CBR system.



Performance trade-off between overhead, mobility, and performance.

(2) Understanding and modeling the fundamental performance trade-offs: We determined that an important performance trade-off is between mobility, overhead, and the performance gains due to accurate measurement of link qualities. The figure above shows this tradeoff when it is assumed that the nodes move randomly and the propagation obeys correlated lognormal fading. Other findings of this work include:

- An analytic model of the performance improvement offered by route diversity.
- The discovery of large performance improvements by moving nodes into locations of optimal propagation.
- The discovery that in dense networks, route performance improves as the number of hops increases.

(3) Sensing the network environment: It is well known that multipath routing can improve the performance in wireline and wireless networks. However, the performance in wireless networks has been reduced by the interference between the routes. In this work, a technique known as Destination-Polling is used to ensure that the secondary path is far from the nodes along the primary path. The specific performance improvements provided by Destination-Polling include:

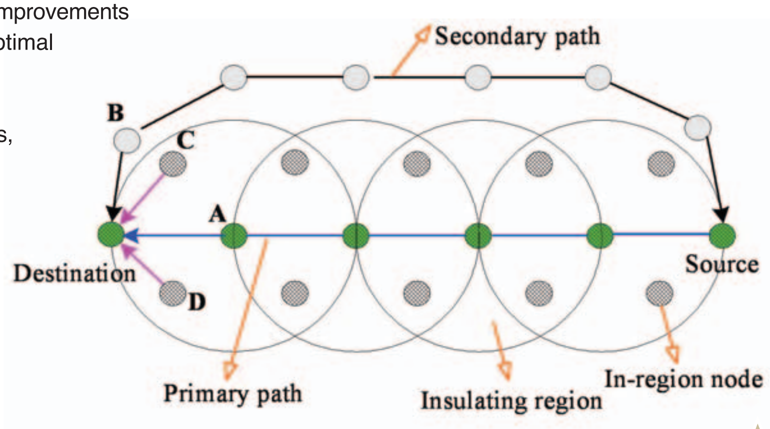
- Higher packet delivery probability.
- Lower end-to-end delay.
- Less out-of-order packet delivery.

PROJECT LEADERS

Dr. Stephan Bohacek, University of Delaware, Newark, DE

Dr. Anthony McAuley, Telcordia Technologies, Piscataway, NJ

Dr. John Baras, University of Maryland, College Park, MD



Destination-polling ensures that routes do not interfere.

COMMUNICATIONS AND NETWORKS

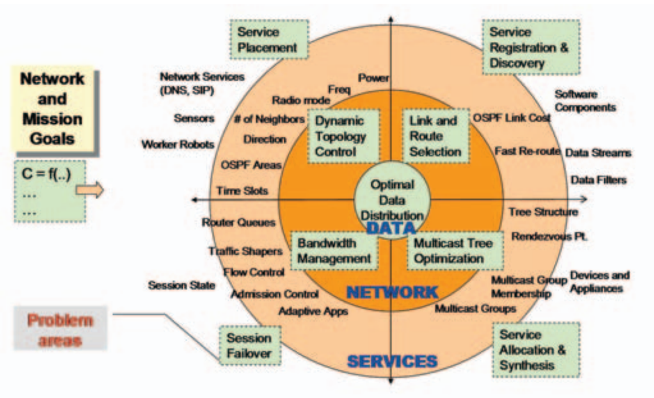
DISTRIBUTED SURVIVABLE RESOURCE CONTROL

DESCRIPTION

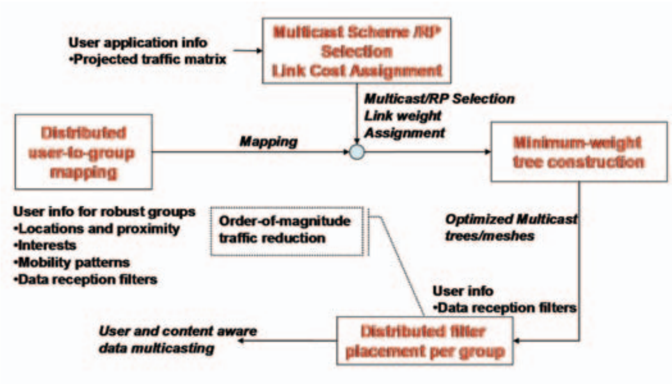
Reliable access to network, services, and data is essential for network operations in FCS UA and Warfighter Information Network-Tactical (WIN-T) Unit of Employment (UE) operations and communications. These resources depend on each other and should be designed accordingly. A need for a comprehensive framework to control resources effectively arises both during deployment to reoptimize the network and at the planning stage to evaluate the impact on network performance. Distributed Survivable Resource Control Tactical (DSRC-T) is a framework intended to improve core networking schemes by controlling and managing their resources. It is likely to employ multiple technologies, each required to be distributed, survivable, dynamic, and secure. The main research thrusts are: (1) Multicast Resource Control for planning and optimizing multicast groups; (2) Quality of Service for multicast flows in red-black networks; (3) mediation among complementary or conflicting control actions; and (4) security issues in distributed resource control.

ACCOMPLISHMENTS

From 2001 to 2006 we have focused on selected special cases of DSRC-T, where controlling resources has meant (1) dynamic discovery and optimal assignment to users and (2) optimal placement of data filters in the network for efficient data dissemination.



DSRC-T problem and research scope.



Overview of data dissemination filter placement.

Research in the former problem area resulted in the Dynamic Survivable Resource Pooling (DSRP) technology, which is implemented as an ad hoc service layer routing scheme that allows for survivability of network services by healing the service layer dynamically. This mechanism provides distributed, scalable, and survivable network service discovery for mobile tactical networks in which distributed information servers and network infrastructure services are forward-deployed and subject to mobility and hostile actions.

- An implementation of DSRP has been demonstrated several times at MILCOM, ARL CTAC, Sarnoff, and CTA reviews.
- Altogether, four journal and over 20 conference papers have been published and two Ph.D. dissertations have been completed at the collaborating universities since 2001.

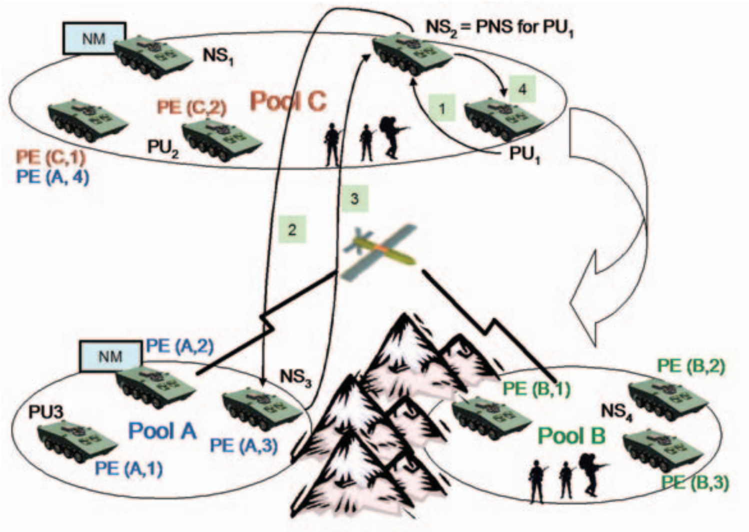
Research in the latter problem area resulted in a generic framework designed to enhance a data-dissemination service through intelligent filtering, configurable collection, aggregation, and scoping of data flows. There are several areas in tactical networks where such efficient data dissemination is required, including application-level multicast communications and network performance statistics as needed by a network management system or network optimization agents. The basic idea is to move filtering actions closer to the data sources, thereby reducing the data dissemination overhead without negatively impacting the capabilities of data users.

- We implemented a simulator of our technology, which we showed at the PILSNER TRL-5 demonstration and several CTA reviews.
- The simulator was transitioned from ARL CTA to PILSNER and delivered to CERDEC.
- As the PILSNER architecture matures and enters the second phase of design and development, transition of the developed efficient data dissemination framework to the WIN-T network targeted by the PILSNER program will be initiated.

PROJECT LEADERS

Dr. Mariusz Fecko and Sunil Samtani, Telcordia Technologies, Piscataway, NJ

Dr. Paul Amer, University of Delaware, Newark, DE



When connectivity to server pool C is disrupted, DSRP technology restores services by using servers in pool B.

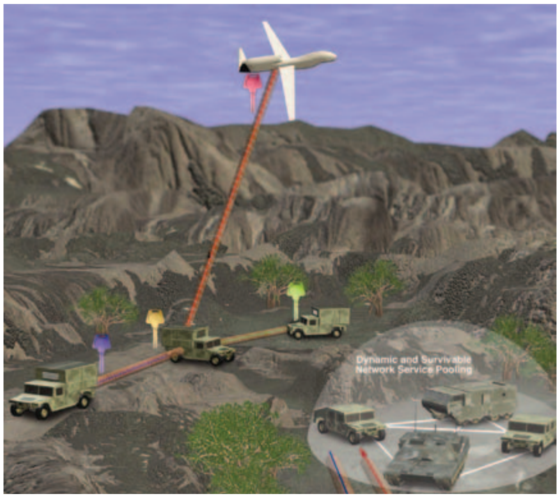
EFFICIENT KEY MANAGEMENT FOR MANETS

DESCRIPTION

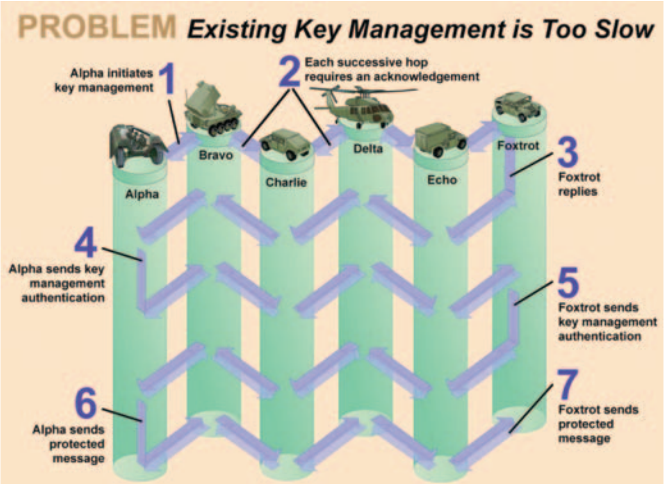
The Efficient Key Management for MANETs project is developing, validating and transitioning new techniques to improve the efficiency, reliability, and survivability of Key Management (KM) in Army MANETs. Such KM techniques are essential for using cryptography to protect tactical networks and applications. In mobile ad hoc environments, traditional KM techniques are inefficient and break down because they:

- Rely on continually available trust-worthy, centralized, infrastructures for key distribution and revocation.
- Cannot tolerate the high end-to-end delays, packet loss rates, bandwidth constraints and asymmetric communications of tactical MANETs.
- Don't consider MANET topologies, Medium Access Control (MAC) layer characteristics (e.g., group/multicast key management).
- Don't take advantage of cooperating MANET nodes to improve their survivability or efficiency.

Our ad hoc networks need neighborhood and end-to-end KM techniques and crypto-protocols that can tolerate the communication environment yet meet the security needs of tactical systems. Well known crypto/key management solutions such as Internet Protocol Security (IPSec) and High Assurance Internet Protocol Encryptor (HAIPE) are not solutions here; their dynamic KM modes are too slow and unreliable for operational tempos, and their static modes are too inflexible for Army systems of systems. We seek alternatives such as using identity-based key-sharing which gives the Army better performing, flexible key management solutions.



Key Management is a critical service for enabling the cryptographic protections needed by Army tactical networks.

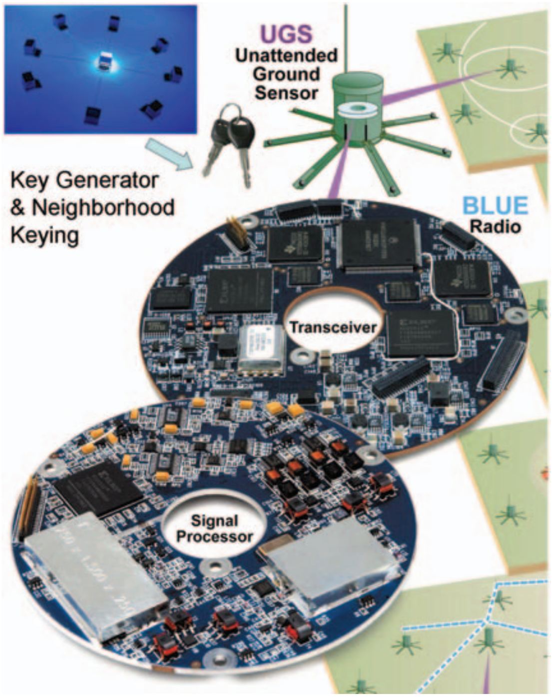


The dynamic key management modes of IPSec and HAIPE are not well suited for use in tactical MANETs. These modes have high latency and low reliability.

ACCOMPLISHMENTS

We have developed many exciting new techniques for key management and support function, including dynamic trust establishment, secure-localization, and low-bandwidth digital signatures. We have also developed new analytical techniques to better understand the security and performance of key management and support functions in ad hoc networks.

- The first practical keying scheme for highly constrained network nodes such as sensor nodes as well as new techniques for revoking keys and detecting misuse of crypto keys.
- New routing algorithms and key management schemes for efficient secure, key management for ad hoc network, multicast communications.
- Digital signatures are an attractive method for authentication key management communications, especially for secure multicast. We have developed techniques for energy efficient verification of low-bandwidth signatures.
- Establishing and revoking trust without good access to a security infrastructure is a challenging problem that becomes more difficult in an MANET. We have initiated the field of Dynamic Trust Establishment (DTE) in MANETs and have developed multiple analytical models of DTE security and performance in ad hoc networks.



Key Management is critical to secure Unattended Ground Sensors (UGS).

PROJECT LEADERS

Dr. Brian J. Matt, SPARTA Inc., Columbia, MD

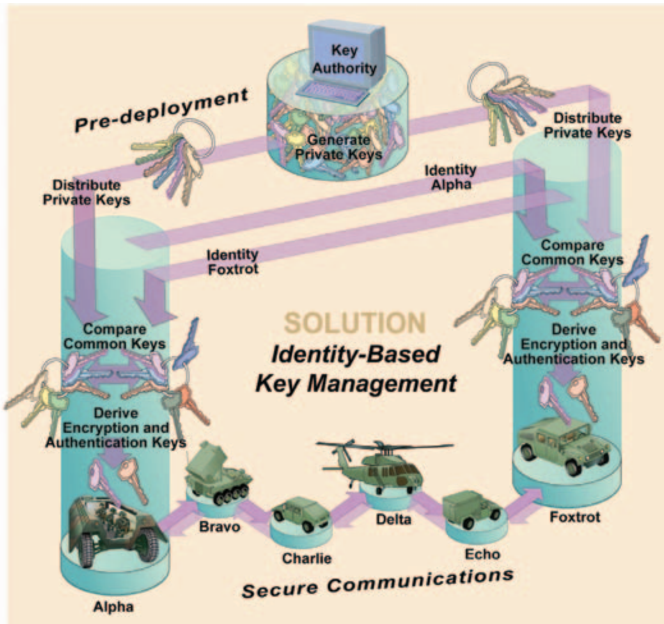
Dr. Virgil Gligor and Dr. John Baras, University of Maryland, College Park, MD

Dr. Radha Poovendran and Dr. Loukas Lazos, University of Washington, Seattle, WA

- We devised new analytical techniques for achieving better understanding of the security of keying schemes for highly constrained network nodes.
- We developed a new low-bandwidth key management technique for use in hierarchies, such as the chain of command, that allow for reconfiguration of the hierarchy in the field (e.g., adaptable to changes in the command structure or unit positions).
- We devised new secure node localization schemes in areas with poor Global Positioning System service which enable more efficient ad hoc KM infrastructures.

In addition, our technology and analyses have been transitioned into the following Army demonstration projects:

- ARL's Secure Mobile Networks project within OSD's Horizontal Fusion program.
- The Army Research Laboratory's unattended ground sensor network (Blue Radio key management subsystem).

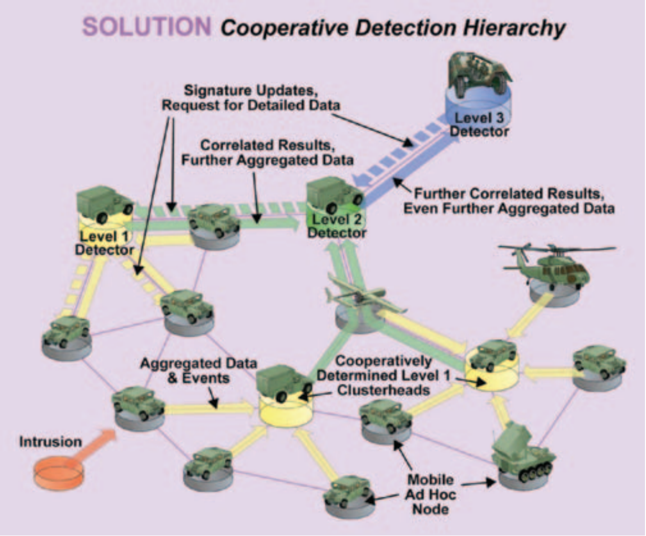


Hierarchical identity-based key sharing technique.

INTRUSION DETECTION FOR MANETS

DESCRIPTION

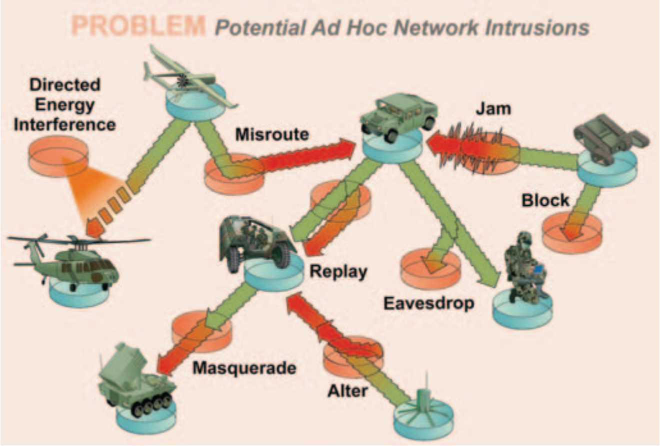
The ability to accurately detect and respond to information warfare attacks in real-time is critical to maintaining the availability of Army tactical networks. Research and development in intrusion detection systems has been ongoing for many years. While some of these efforts have been successful in detecting various network attacks against dedicated hosts on fixed networks, they have proven to be ineffective in identifying complex network attacks in wireless mobile ad-hoc networks (MANETs). Within a MANET, attack symptoms can be dispersed with no single good location to monitor network traffic. Also, unreliable wireless links may limit what network monitors can see and make centralized security management components unreachable. Limitations in network bandwidth constrains the amount of intrusion data that can be exchanged. Despite these constraints, it is important to be able to detect attacks and localize their sources quickly and accurately.



Cooperative intrusion detection hierarchies are efficient and reduce bandwidth consumption.

ACCOMPLISHMENTS

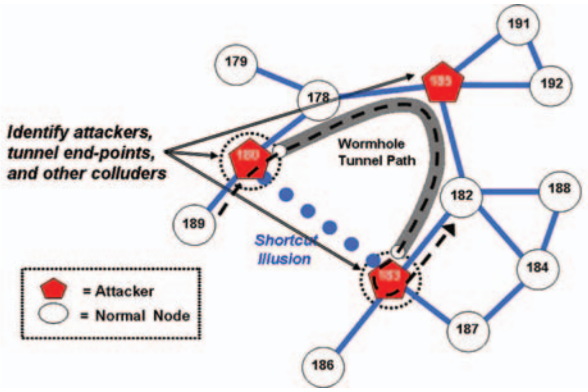
We have focused our research on several key areas that address the problem of detecting attacks within a MANET: (1) improving the efficiency of the intrusion detection infrastructure for collecting and analyzing intrusion data; (2) developing methods for detecting complex multi-stage attacks, and (3) developing detection techniques for attacks involving collusion among compromised insider nodes.



Army networks are vulnerable to numerous types of cyber attacks.

To improve the efficiency of the intrusion detection infrastructure, we designed algorithms and protocols for data aggregation and dissemination that reduce bandwidth consumption by distributed detection components. We also developed specialized clustering algorithms that organize the MANET into a cooperative detection hierarchy of nested, topological regions in which the clusterhead chosen for each region gathers and consolidates intrusion detection data within the region and forwards it up the hierarchy.

Monitoring traffic within a distributed MANET environment using centralized sensors is impossible. Attack evidence may be scattered and difficult to identify and/or coalesce. Our research addresses this problem by applying compositional fuzzy reasoning techniques to provide robust reasoning under the uncertainty of tactical environments. We also applied these techniques to reason about recovery from attack. To enable more complete and rigorous detection of attacks on MANET routing, we developed formal, specification-based intrusion detection techniques that determine whether network-wide security properties are satisfied by monitoring local



Detecting “wormhole” cyber attacks.

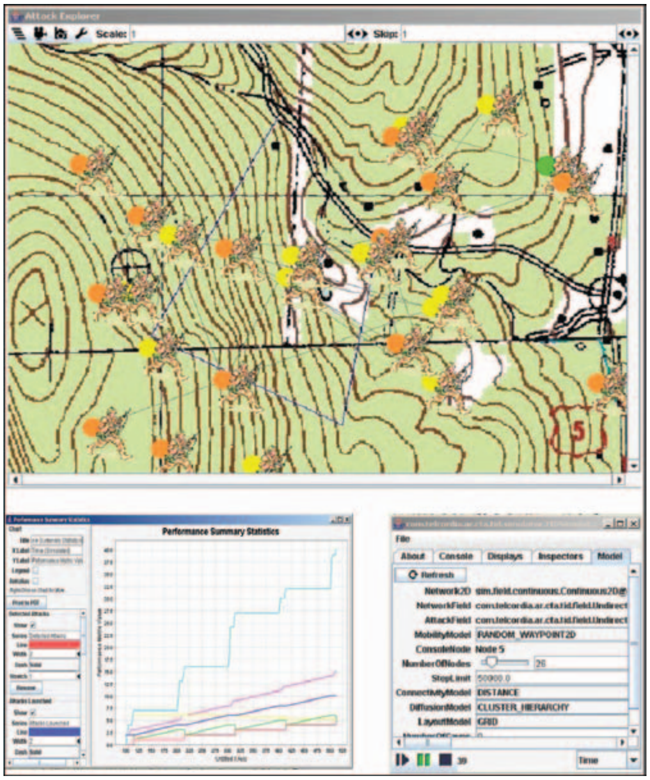
PROJECT LEADERS

Mike Little, Telcordia Technologies, Piscataway, NJ

Dan Sterne, SPARTA, Columbia, MD

behavioral constraints at individual nodes. Finally, we defined a completely decentralized and cooperative approach to signature-based detection that is capable of detecting complex (multi-participant multi-staged) attacks.

When attackers collude, the challenges of detecting attacks on a tactical MANET become substantially more difficult. Multiple attacking nodes operating in collusion can corroborate each other’s lies to provide a degree of consistency that may foil some detection mechanisms. To counter this threat, we developed detection techniques for collusion attacks against the MANET routing protocol OLSR, specifically the in-band wormhole attack. To analyze the effect of a wormhole attack on routing, we developed a novel methodology called gravitational analysis, which quantifies wormhole cost, attraction, potential detectability and other related measures for paths, nodes, and topologies. Also, in a more theoretical effort, we developed techniques that treat a collection of attackers as a concurrent system and have adapted concurrency theory methods to probabilistic models of concurrent systems.



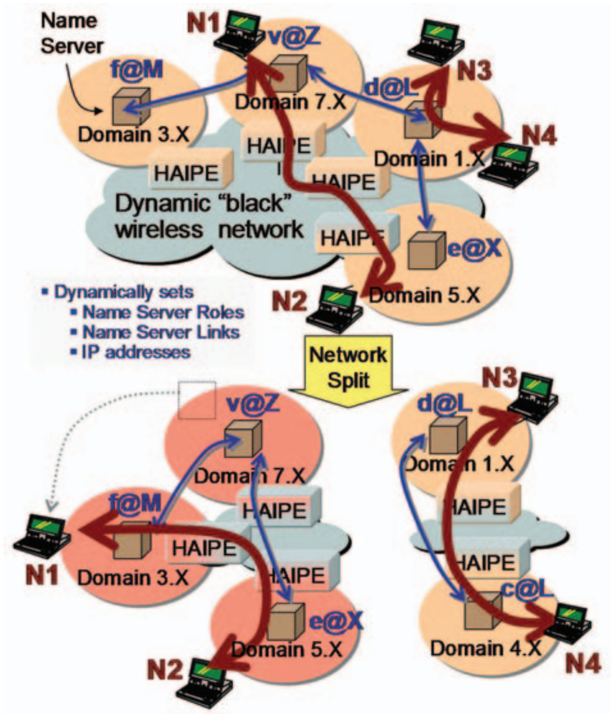
Network attack visualization.

COMMUNICATIONS AND NETWORKS

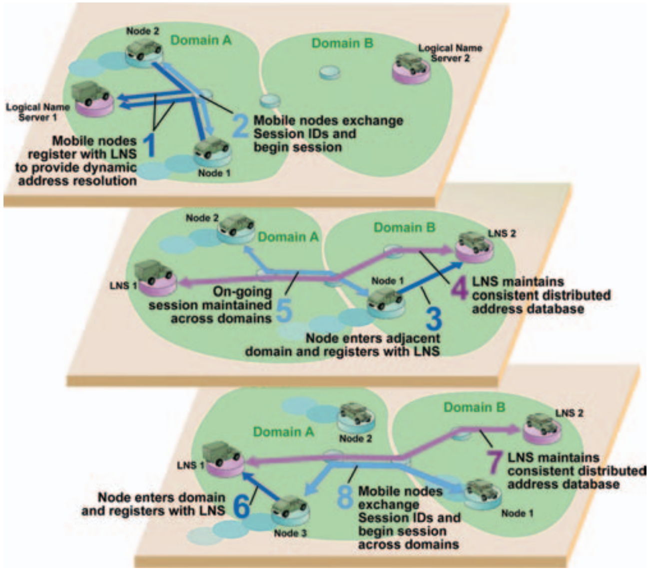
MOBILITY AND LOCATION MANAGEMENT FOR MOBILE AD HOC NETWORKS

DESCRIPTION

Dynamic military ad hoc networks such as the Future Combat System (FCS) and Warfighter Information Network-Tactical (WIN-T) must allow nodes to locate and communicate with any other node for which a routing path exists. Even with good engineering (e.g. using redundant servers) existing commercial IPv6 mobility and location management solutions, such as Mobile Internet Protocol (MIP) and Domain Name System (DNS), may be fragile and perform poorly. To meet the challenges posed by the Network Centric Warfare paradigm, mobility solutions must be efficient, interoperable and support autonomous disconnected operations. The figure below shows an example of linkage to and among Name Servers without reliance on root/home servers nor brittle relationships among servers. Our goal has been to create fundamentally better solutions, enabling Warfighters to maintain sessions and reachability in extreme conditions. Just as important, we provide military planners with confidence in the solutions and the tools to quantifiably tradeoff competing approaches.



Name server support for autonomous, disconnected operations.

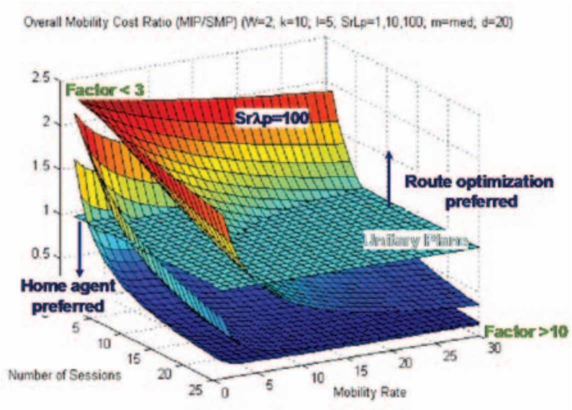


Logical Name System (LNS) for dynamic ad hoc networks.

ACCOMPLISHMENTS

We have designed a new Logical Name System (LNS) (see figure above), that is more auto-configurable, robust and flexible than the current Domain Name System (DNS). Nodes, services, multicast groups, or users, can be autoconfigured with multiple, abstract names. LNS automatically provides the best dynamic Internet Protocol (IP) address(es) of each reachable entity, while providing for authentication and authorization. Even with large networks that dynamically split into isolated islands, LNS reconfigures LNS servers and their links so almost 100 percent reachability is achieved, compared with under 10 percent reachability for a DNS system (with root and master Name Servers). Additionally, we have designed a name and address decoupling approach based on the use of a Session Identifier (SID) that significantly improves performance during address changes, as binding updates can be securely sent by in-band signaling.

Using the knowledge of LNS/SID, we identified DNS weaknesses and proposed ways to improve on DNS design taking into account mobile ad hoc network requirements. In particular, we provided techniques to minimize the effect of intermittent connectivity, perform quick updates and resolutions and minimize the bandwidth to replicate databases.



Analysis of the performance tradeoffs with route optimization.

Although many key elements of future force have been developed, many have never been tried on a large scale. It is unproven whether these elements will be able to maintain network performance and reliability as networks grow and mobility increases. To overcome the lack of formal methods for objective comparison of different approaches, we have developed a new framework for analyzing mobility and location management protocols such as Mobile Internet Protocol (MIP) and Domain Name System (DNS).

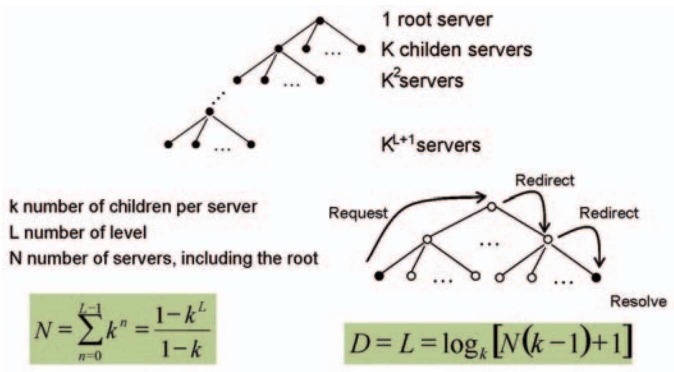
- Mobile Internet Protocol (MIP): We have developed models to allow quantifiable cost and performance comparison of different approaches to mobility management. The results help to identify which protocols are optimal under specific conditions and requirements. The figure above shows an example of the effect of mobility rate and number of sessions by plotting the overall cost ratio between a home agent based approach and a route optimization. While route optimization saves at most 3x in overall mobility cost, the use of dynamic home agents can result in over 10x reduced cost.

- Domain Name System (DNS): We have developed a simple model of DNS and its search system (see figure right). When server mobility is limited to leaf servers, a flat DNS hierarchy gives better performance as the diameter D (maximum number of hops) for a search is minimized. But when non-leaf DNS servers are also mobile, a flat hierarchy entails a large number of link updates upon a move. Hence, increasing the levels of hierarchy gives a better performance.

The analytical analysis carried out has exploited a multidisciplinary approach, with collaboration between mathematicians and protocol researchers. The models have been transitioned into the CERDEC, Network Design project to help quantify the performance and cost of different mobility management solutions. The work has produced six conference papers at MILCOM, PIMRC and VTC.

PROJECT LEADERS

Dr. Raquel Morera and Dr. Anthony McAuley, Telcordia Technologies, Piscataway, NJ



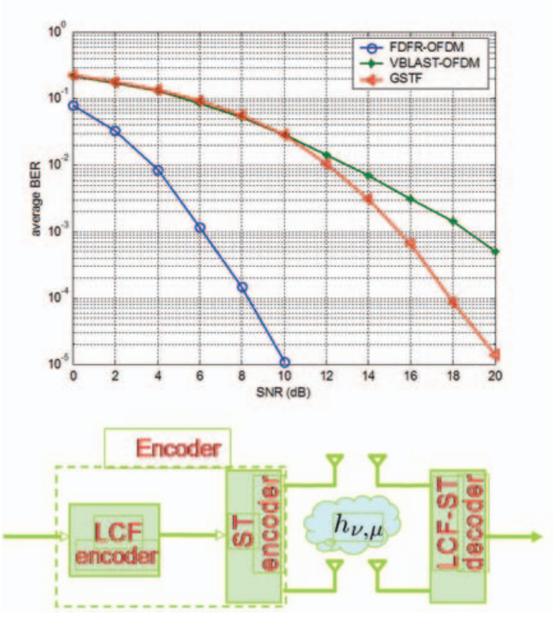
DNS model and DNS search model.

COMMUNICATIONS AND NETWORKS

MULTI-CARRIER TECHNIQUES

DESCRIPTION

Multi-carrier (MC) radios employ orthogonal frequency division multiplexing (OFDM) to convey information riding on digital sub-carriers. Multi-carrier techniques can be used for point-to-point or multiple access (OFDMA) systems, with single- or multi-antenna transceivers. Multi-carrier tactical radios offer numerous benefits: they can cope with multipath fading propagation; they can use simple equalization and decoding to improve transmission/reception; they can allocate rate and spectrum efficiently (over non-contiguous bands); and they are agile to avoid various sources of interference. Our multi-carrier techniques aim can be employed in high rate Warfighter radios and OFDM based wireless sensor networks to overcome key technical barriers (such as sensitivity to carrier synchronization, non-constant modulus and loss of diversity) while maintaining desiraable characteristics of low-power, adaptation to the environment, anti-jamming, and low-probability of detection and interception.



FDFR MIMO-OFDM architecture. Bottom: Significant bit error rate gains over the V-BLAST MIMO-OFDM benchmark architecture.

ACCOMPLISHMENTS

We have made numerous research accomplishments:

- By using embedded synchronization patterns, we are able to increase spectral efficiency at high hop rates and facilitate channel estimation with superimposed and inserted pilots.

- We can improve the longevity and survivability of battery-operated tactical orthogonal frequency division multiplexing (OFDM) radios by optimizing the peak-to-average power ratio (PAPR) and thereby obtaining efficient power amplification.

- We have developed linear complex field (LCF) precoders to regain the lost multipath diversity of OFDM transmissions over multipath fading channels without rate loss. LCF precoded OFDM enables maximum singal diversity and allows for dynamic control over diversity-complexity tradeoffs. LCF precoders outperform more traditional Galois Field (GF) coders over fading channels. However, since GF coders are better than LCF precoders for additive white Gaussian noise links, we developed a joint GF-LCF coder with turbo decoder that can take advantage of these characteristics.

- We thoroughly delineated the tradeoffs between single-carrier (SC) and multi-carrier (MC) techniques and established that zero-padded block SC transmissions offer several benefits: maximum diversity and coding gains; obviate the peak-to-average power ratio (PAPR) problem; are less sensitive to carrier synchronization; and have affordable decoding complexity using Viterbiís algorithm. We also determined that SC should be chosen over MC techniques when high-rate error control codes are used, whereas MC radios should be preferred with low-rate codes, due to their simplicity.

- Channel variation within an OFDM block arises due to mobility and causes undesirable inter-carrier interference (ICI) effects but also provides an extra dimension of (Doppler) diversity. We developed anti-jam transmit waveforms and low-complexity OFDM receivers to effectively suppress ICI; collect the Doppler diversity; and gain robustness to multipath fading narrowband interference (NBI) jamming. Multi-carrier spread-spectrum (SS) was shown to outperform direct-sequence SS.

- We devised space-time-frequency (STF) codes for multi-antenna OFDM transmissions over (possibly correlated) multiple-input multiple-output (MIMO) fading channels. Using linear complex field (LCF) and STF (de)coding, a full-diversity full-rate (FDFR) milestone architecture has been developed to collect the available diversity and coding gains. Furthermore, it is applicable to any number of transmit-receive antennas, and flexible enough to attain desirable tradeoffs in diversity rate-complexity.

- We developed a unifying multiple access scheme that can be configured using software radio transceivers to act as orthogonal frequency division multiple access (OFDMA), time/frequency/code division multiple access (TDMA, FDMA, CDMA) and all available hybrids such as MC-CDMA, TDM-FDMA, OFDM-TDMA including ultra-wideband (UWB) OFDMA variants. Its attractive features include resilience to various sources of (un) intentional interference; the ability to collect the available transmission diversity; bandwidth efficiency and rate scalability. Unitary Precoded OFDMA (UP-OFDMA) is a particularly desirable generalized mult-carrier technique since it is also power efficient and is flexible to avoid jamming-induced interference.

- MAC layer and cross-layer designs of MC networks: opportunistic and energy-efficient protocols have been developed for MC based access, scheduling and resource allocation in collaborative MANETs.

- We have tailored multi-carrier techniques for several Army programs including: the joint tactical radio system (JTRS) cluster 5, the Navy digital modular radio, DARPAís CN and XGEN programs, CERDEC's MOSAIC and MARCON-i programs and the wideband network waveform (WNM) for the Future Combat System (FCS).

PROJECT LEADERS

Dr. Georgios B. Giannakis, University of Minnesota, Minneapolis, MN

Dr. Ye (Geoffrey) Li, Dr. Xiaoli Ma, Dr. Gordon Stuber,

Dr. G. Tong Zhou, Georgia Institute of Technology, Atlanta, GA

Dr. X.-G. Xia, Dr. Len Cimini, University of Delaware, Newark, DE

Dr. Ray Liu, Dr. Sennur Ulukus, University of Maryland, College Park, MD

Dr. Vincent Poor, Dr. Sergio Verdu, Princeton University, Princeton, NJ

John Kleider, General Dynamics C4S

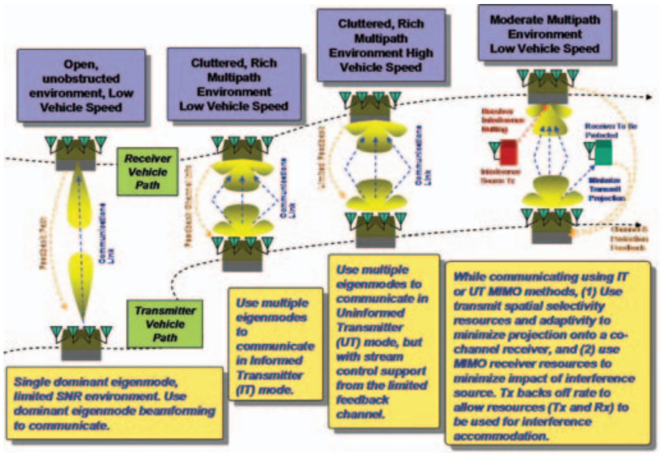
Top: Wideband OFDM Cluster 5 Prototype (General Dynamics). Middle: Abrams tank original image (left); compressed, Tx w/ WB-OFDM and Rx (right); modified PRC-112 pilot radio. Bottom: possible insertion devices (manpack and WSNs).

COMMUNICATIONS AND NETWORKS

MULTI-INPUT MULTI-OUTPUT (MIMO) SYSTEMS

DESCRIPTION

Nearly a decade after its introduction, Multiple-Input Multiple-Output (MIMO) systems, a key enabling technology for high performance high rate wireless communications, is rapidly moving from the theoretical to the practical realm. Using multiple antennas at both ends of the link, MIMO technology exploits the additional spatial dimension, offering benefits previously not realizable using single antenna links. Benefits include high data-rate communications in limited bandwidths, more robust wireless communications, significant range extensibility, greater security (both from an intercept and detectability standpoint), and the ability to adapt to changes in both the propagation environment and quality of service (QoS) requirements. Today, the application of MIMO technology is being considered for indoor local area networks, cellular multimedia data networks, broadband fixed and mobile wireless access, and tactical mobile-to-mobile ad hoc wireless communication networks.



MIMO modes of operation.

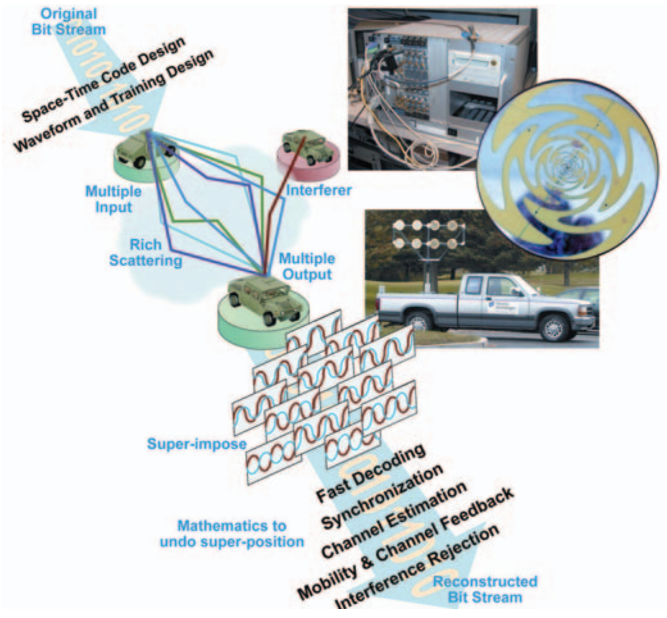
ACCOMPLISHMENTS

MIMO research activities in the CTA have spanned the gamut from signal processing and algorithm design to extensive over-the-air measurement based performance analyses and real-time testbed development. Together, they have resulted in significant advances in state-of-the-art of MIMO technology, promising unprecedented mobile wireless networked throughput in a crowded electromagnetic environment comprising both friendly interference and jamming.

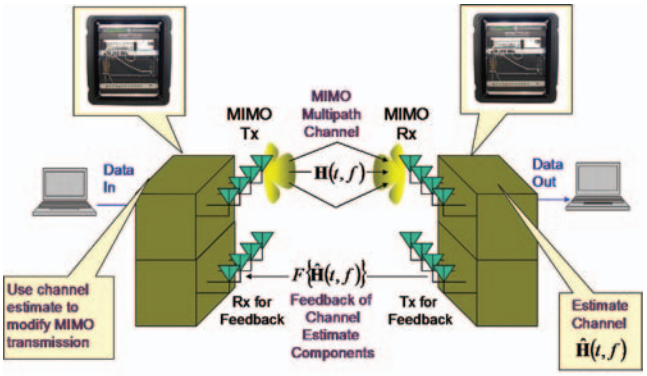
- For high-rate MIMO, the conventional detector for near-optimal performance is computationally prohibitive. With a view to enabling practical implementations of high-rate MIMO, we have developed novel detectors that can be flexibly configured to deliver the best possible combination of performance and complexity over a wide range of realistic operating conditions.

- Previously, the rate-enhancement and energy-efficiency (or diversity enhancing) aspects of MIMO were not tackled simultaneously. In the CTA, space-time codes that offer both these benefits simultaneously have been developed.

- In scenarios with high node mobility, there is an increased overhead for channel tracking that reduces the throughput and/or increases the receiver complexity. Differential space-time coding methods that work in



MIMO system concept.



Channel estimation for MIMO transmission.

conjunction with iterative detection have been devised to support channel-blind, high-performance detection in these highly dynamic scenarios. Results have also been developed to exploit partial or imperfect channel knowledge at the transmitter to perform adaptive modulation to further maximize performance, particularly in the presence of jamming.

- One of the concerns for tactical communications is that of antenna size, which becomes particularly problematic for arrays at high frequency. Combining precoding methods at the transmitter and near-optimal iterative processing, we have made possible the use of fewer transmit and receive antennas than the number of transmitted streams. These methods also allow jammer excision and interference avoidance while maintaining a low array profile.

- We have also explored methods to realize virtual MIMO using distributed antennas/nodes. This helps with the antenna size as well as realizing MIMO benefits using multiple low-powered distributed man-portable radios.

- Lack of proper resource coordination at the network level can result in significant loss of MIMO diversity and spatial multiplexing gains due to the interference from other users. We have developed a MIMO-aware MAC protocol to maintain MIMO benefits in a network of MIMO users.

- Finally, several of these innovations have been tested in over-the-air experiments. Measurements have demonstrated the feasibility of rates exceeding 25 bps/Hz. MIMO measurements have also provided a large body of real-world channel data that can be used to build analytical channel models suitable for MIMO system design and performance evaluation.

PROJECT LEADERS

Dr. John Koshy and Dr. Joseph Liberti, Telcordia Technologies, Red Bank, NJ

Dr. Georgios Giannakis, University of Minnesota, Minneapolis, MN

John Kleider, General Dynamics C4 Systems, Atlanta, GA

Dr. Thomas Pratt, Georgia Tech Research Institute, Atlanta, GA

Dr. Brian Sadler and Dr. Ananthram Swami, ARL, Adelphi, MD

MIMO technology provides robust high data-rate communications in challenging signal environments.

COMMUNICATIONS AND NETWORKS

SENSOR NETWORKS

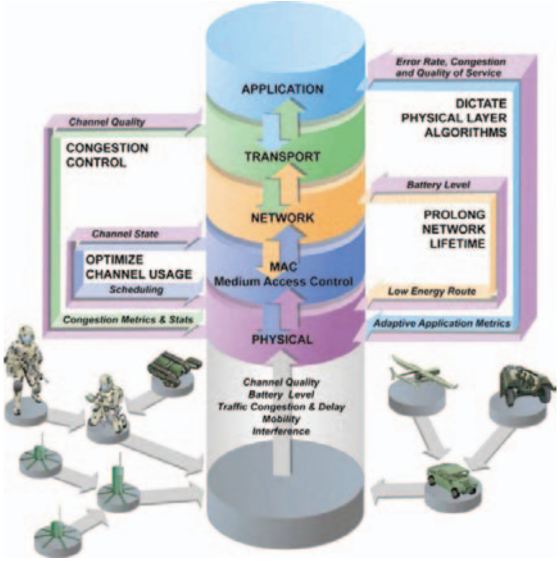
DESCRIPTION

Sensor networks are a key element of Future Force network centric operations. A fundamental difference between sensor networks and conventional infrastructure-based networks or mobile ad hoc networks (MANETs) is that sensor networks are application specific. Therefore what is important is how the network performs a particular set of tasks rather than how the individual nodes are served. This difference means traditional approaches for network design and optimization are not applicable.

Our research aims to develop new networking paradigms for application specific sensor networks that achieve overall network performance under severe energy and bandwidth constraints. Specifically, our research focuses on several novel techniques:

- Distributed target detection and tracking using wireless sensor networks.
- Cooperative networking for bandwidth and energy efficiency.
- Cross-layer design for large-scale sensor networks.

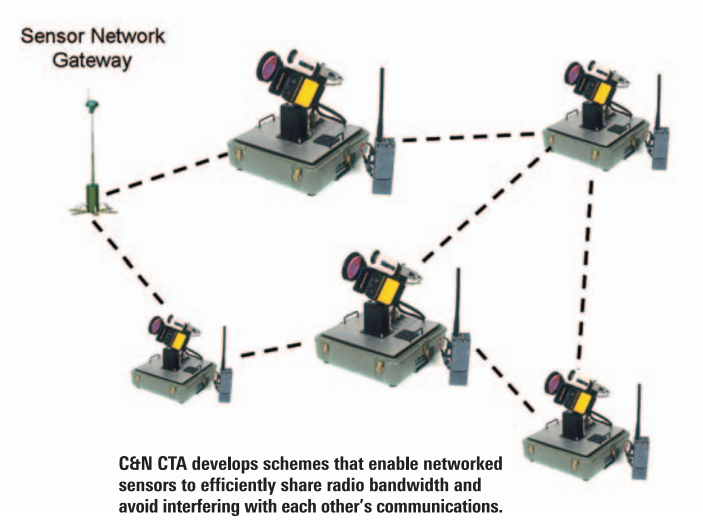
Networked sensors in situ must operate with low power consumption and highly efficient communications to preserve battery life and avoid enemy detection.



Cross-layer techniques for sensor networking.

ACCOMPLISHMENTS

- Sensor networks with mobile access: We devised a network architecture to reduce network overhead and minimize sensor node energy consumption by introducing multiple mobile access points to sensor networks. We developed simple distributed sensor access schemes and collaboration schemes for mobile access points that asymptotically achieve optimal throughput.
- Data centric multiple access: Conventional multiple-access schemes for wireless networks focus on throughput and delay metrics. However for sensor networks, application specific measures such as miss detection and false alarm rates are the key performance metrics. Therefore, we developed a type-based multiple access scheme that is data-centric rather than user centric, thereby achieving a significant gain in energy efficiency.
- Blue MAC for Blue Radio networks: ARL developed the Blue Radio to provide efficient communications with low power consumption in sensor applications. We have developed efficient medium access control schemes for Blue Radio that provide energy efficient synchronization, and duty-cycling.



C&N CTA develops schemes that enable networked sensors to efficiently share radio bandwidth and avoid interfering with each other's communications.

- Cross-layer design for energy efficient resource allocations: Energy efficiency is crucial for tactical radio networks. We have developed energy efficient resource allocation schemes based on cross-layer optimization that exploit partial or full channel state information.

- Opportunistic spectrum access: Conventional access schemes to support large-scale sensor network require pre-defined radio spectrum allocation. However, because sensor network traffic is bursty, fixed spectrum allocation can lead to inefficiency. We have developed new opportunistic spectrum access schemes that take advantage of spectrum white space in frequency bands allocated to other primary users.

- Cross-layer design for cooperative communications: Cooperation among sensor nodes can significantly enhance network performance and reduce energy consumption. We explored the use of relays to support cooperation and devised multiple access schemes that jointly optimize physical layer and medium access control performance.

- Sensor network security: Sensor networks are not physically secure. Sensors may be captured and reprogrammed to launch the so-called Byzantine attack or insider attack. We have identified numerous attacking strategies and corresponding countermeasures.

- Link metric for optimal target detection: A key characteristic of using sensor networks for target detection and tracking is that sensor measurements are spatially correlated. We developed a new link metric for multihop sensor networks that helps optimize detection performance and energy efficient data aggregation.

PROJECT LEADERS

Dr. Lang Tong, Cornell University, Ithaca, NY

Dr. Prithwish Basu and Dr. Jason Redi, BBN Technologies, Cambridge, MA

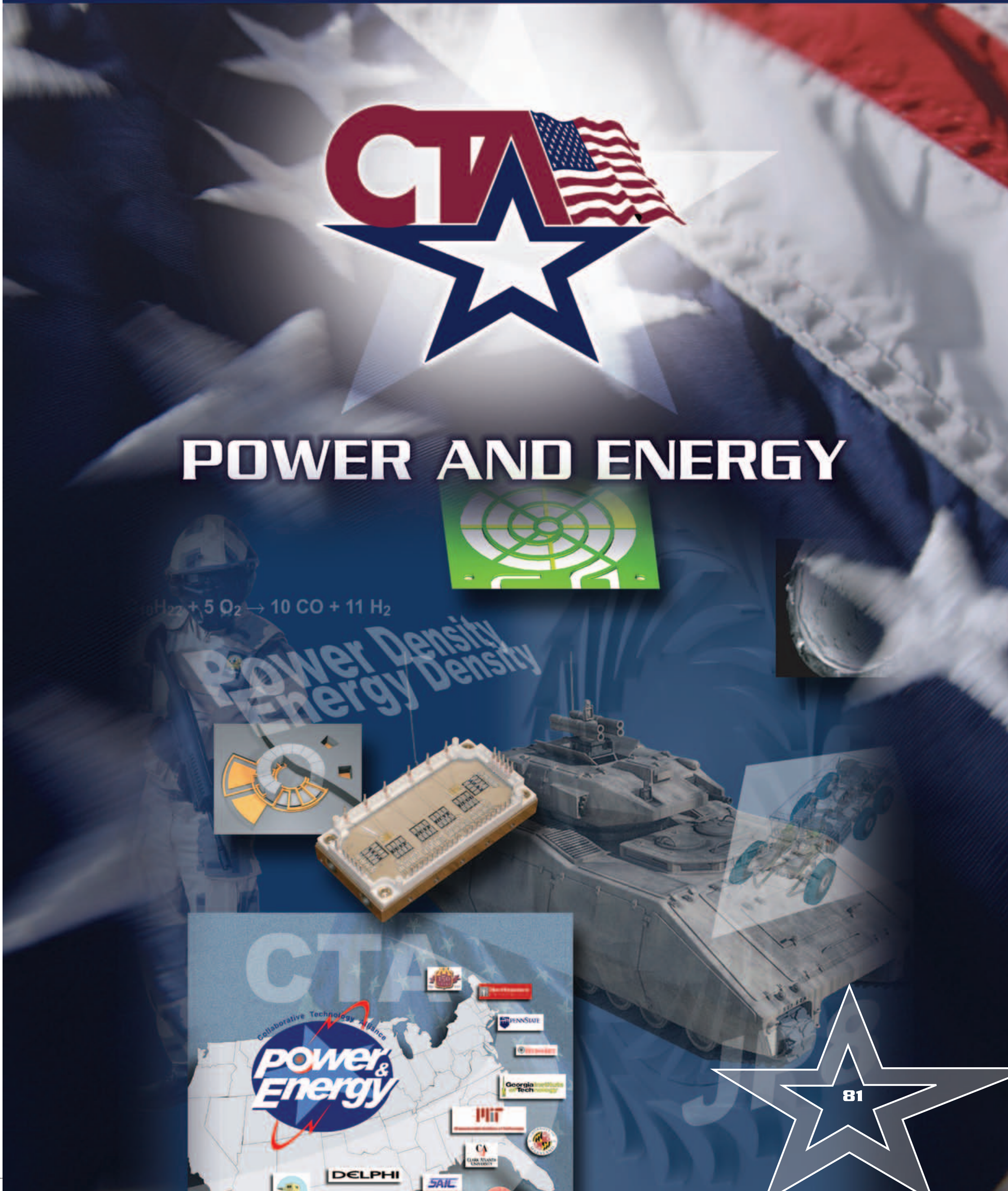
Dr. Anthony Ephremides and Dr. K.J. Ray Liu, University of Maryland, College Park, MD

Dr. Georgios Giannakis, University of Minnesota, Minneapolis, MN

Dr. Qing Zhao, University of California at Davis, Davis, CA

C&N CTA researches techniques that allow only authorized users to access sensor network communications.

POWER AND ENERGY



POWER AND ENERGY

POWER AND ENERGY CTA OVERVIEW

OBJECTIVES

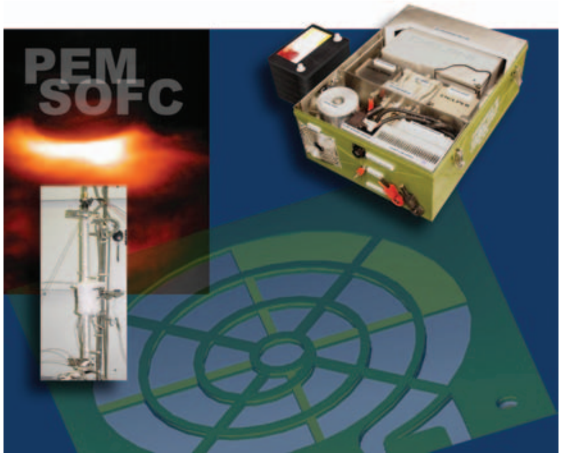
This six-year research effort is intended to demonstrate an operating microfabricated gas turbine engine and electric generator. These devices would provide proof-of-concept of the capabilities of power Micro-Electro-Mechanical Systems (MEMS), and demonstrate the feasibility of evolving this technology into a micro-gas turbine generator in a package of a few cubic centimeters, running on a hydrocarbon fuel.

Research in the area of fuel cells and fuel reformation is aimed at improving the performance and energy density of fuel cells for portable power systems and developing logistic fueled power systems for mobile and stationary requirements. Portable fuel cell systems are capable of a 5-10 fold increase in storage capacity over current batteries while requiring less than a quarter of the fuel. Logistic fueled power systems would be a minimal logistical burden while extending the time and range of operations.

A Hybrid Power system, one that combines the best features of mechanical and electrical power, will enable FCS to meet the requirements and all elements of the Army vision and will be served by developing a Combat Hybrid Power System. The goal is to develop the component and device technology for the subsystems and systems that will make hybrid electric combat power systems practical and efficient.

TECHNICAL AREAS

This proof-of-concept power MEMS will demonstrate that a micro-gas-turbine generator may do the following:

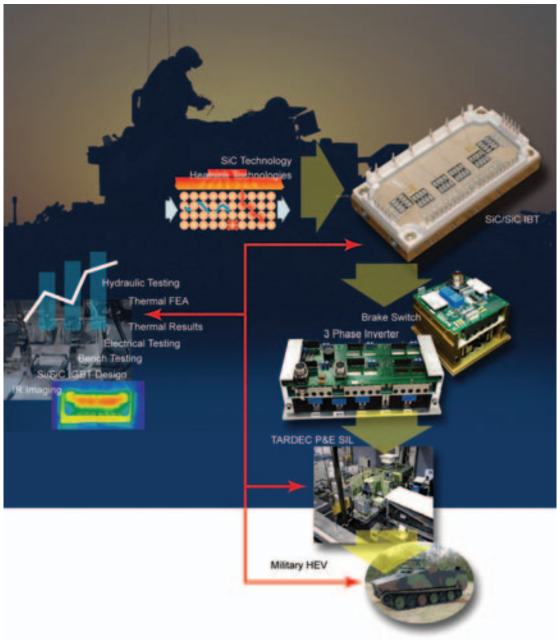


- Decrease the mass of Soldier power systems by two to four times in the near term and up to 10 times in the longer term.
- Reduce the logistics burden by eliminating the battery logistics.
- Reduce the life-cycle cost of Soldier power by an order of magnitude or more.

The expected outcomes of research in the area of fuel cells and fuel reformation include:

- High power density, compact, lightweight, and highly efficient power systems.
- Proton Exchange Membrane Fuel Cells (PEMFCs) for compact power sources with methanol.
- Portable power systems that will increase the power available by a factor of two to three.
- Solid Oxide Fuel Cell (SOFCs) that operate on logistics fuels.
- Compact systems for reforming logistics fuels.
- Regenerative desulfurization systems for logistics fuels reforming.

The focus on Silicon Carbide (SiC) Materials and Devices is to improve the quality of the materials used to make SiC devices. This includes improving the quality of the oxide and the oxide semiconductor interface, the material



quality of the implanted device structure, and contacts to the device. The focus on Small Hybrid Power Systems (HPS) is the development of an Active HPS for small robot systems.

ACCOMPLISHMENTS

Power MEMS

Developed gas bearings for Power MEMS. Developed hydrostatic gas journal and thrust bearings demonstrated by spinning a 4.2 millimeter (mm) diameter silicon rotor to 1.7 million revolutions per minute (rpm). Developed revolutionary gray-scale process technology that allows arbitrary etch depth variation, greatly extending the design space. Demonstrated silicon wafer fusion bonding of wafer stacks of up to 10 wafers. Demonstrated high-power-density MEMS magnetic motors and generators operating in the 10 watt range.

SOFC/Reformation

Demonstrated that fuels such as JP-8 and diesel fuel can be reformed very efficiently and simply over long time periods. The products formed can be used directly in SOFC. New technology has been developed which provides for on-board sorbent sulfidation/regeneration for SOFC.

Metal Hydride Fuel Cells

Demonstrated scalable fuel cell technology from 10 mW, 3 Volt (V) fuel cell to 300mW, 4.5V fuel cells with a very high specific energy many times that of lithium primary batteries. By making combat system driven by new power technology using SiC electronics, future combat system can be very efficient, mobile, and capable of carrying additional Soldiers, fuel or ammo.

Development of a Li-ion power pack with twice the energy density and 25 percent lighter than the existing power pack. Developed a Direct Methanol Fuel Cell (DMFC) Li-ion Hybrid power source to allow field charging of the battery and enhanced vehicle readiness.

PARTNERS

Honeywell, Lead Industrial Organization for P&E CTA

Industrial Partners

Brookhaven National Lab
Honeywell, DuPont, Motorola Labs,

University Partners

Clark Atlanta University
Georgia Tech
Massachusetts Institute of Technology
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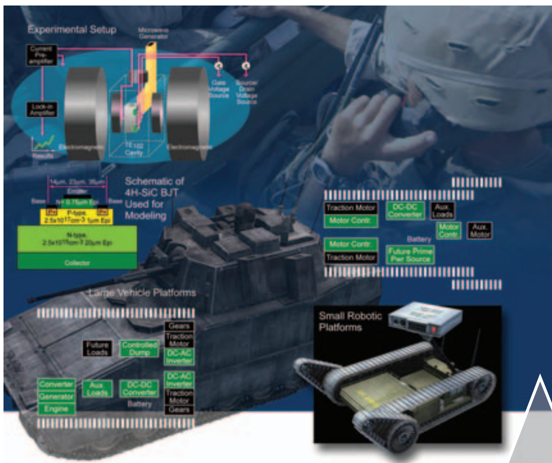


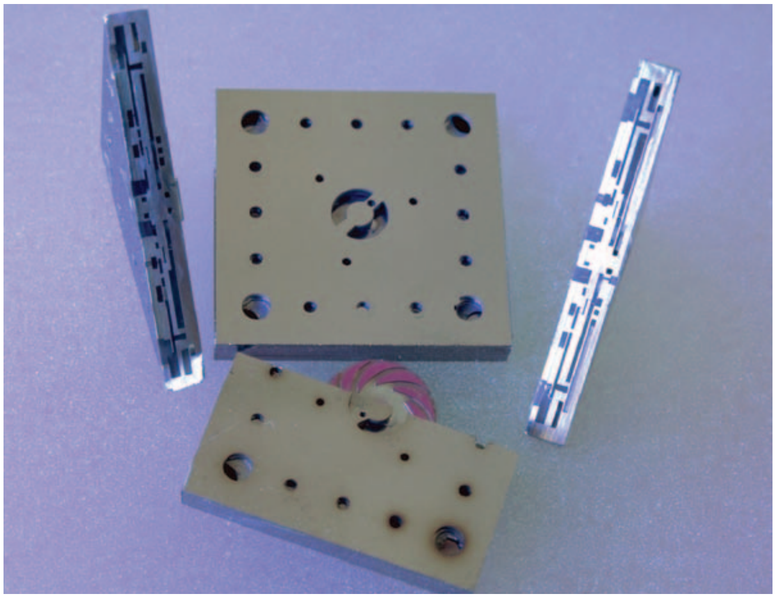
POWER AND ENERGY

POWER MEMS COMPONENT TECHNOLOGIES

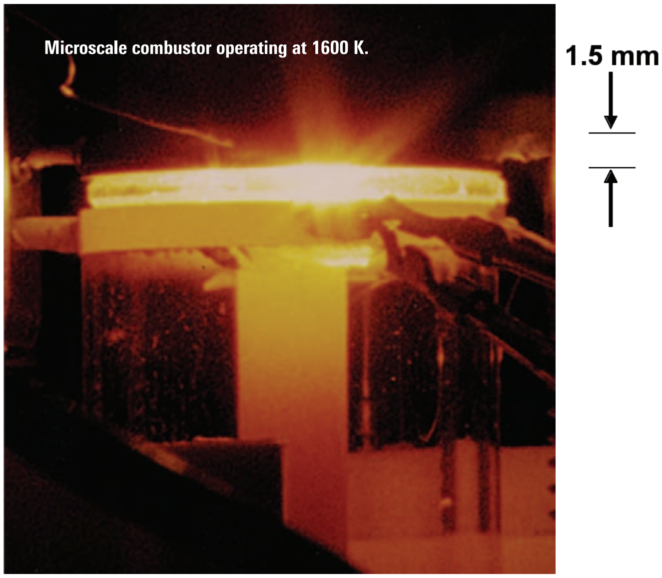
DESCRIPTION

Power MEMS is a new field aimed at developing small-scale devices that operate at multi-watt power levels. Scaling devices, such as an engine, down to the size of a button allows for power densities that far exceed what would be possible at conventional scale. MEMS devices are typically fabricated from silicon wafers using processes borrowed from the computer-chip industry, enabling high volume/low cost production. We have developed components for a MEMS gas turbine generator that would serve as a battery replacement for the Soldier, dropping energy supply system weight by a factor of 5-10, significantly impacting the load that a Soldier needs to carry. The components developed are fundamental to a broad range of mechanical systems and could be transitioned into other Soldier-relevant devices such as micro-coolers, turbine-generators, pumps, blowers, and motors.

The CTA focused on a range of MEMS component technologies, including combustors, bearings, motors/generators and turbomachinery. The fabrication capabilities of MEMS for high power density devices is still quite limited, leading to design tradeoffs between device complexity and performance. The CTA also funded development of new cutting edge fabrication processes that have improved the achievable complexity level, providing an increase in expected device performance.



Silicon multilayer turbocharger devices.

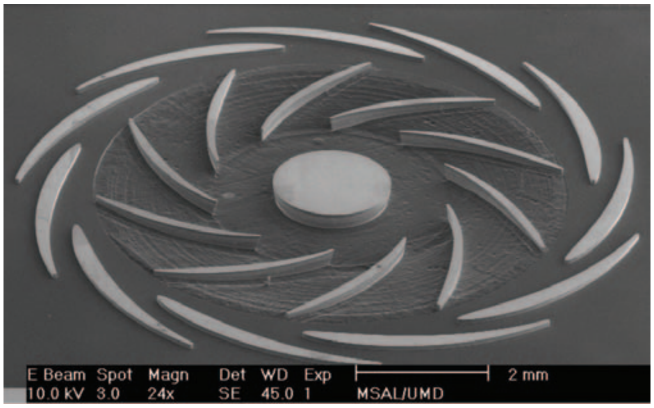


Microscale combustor operating at 1600 K.

ACCOMPLISHMENTS

Small-scale combustion is a challenge as small volume limits the residence time of reactants in a combustor. In this program, we showed that a gas-phase combustor burning hydrocarbon fuels would be impractical for our MEMS gas turbine. We demonstrated low pressure loss catalytic combustion of gaseous propane in a microcombustor at modest efficiency levels; our models indicate how to improve efficiency in future designs. We are now developing a jet propellant (JP8)-fueled MEMS combustor as a logistic fuel that is best suited to Soldier application. A model of JP8 vaporization was developed and verified experimentally. We also developed a model of JP8 catalytic combustion and are now building a MEMS JP8 combustor test stand with vaporizer to verify this model. In particular, we will explore fuel vaporization, coking and efficiency.

This program is the world leader in gas bearings for Power MEMS applications. Hydrostatic gas journal and thrust bearings have been developed and demonstrated by spinning a 4.2 mm diameter silicon rotor to 1.7 million rpm, equivalent to a tip speed of 370 meters per second (m/s). This demonstration is over an order of magnitude faster than any other MEMS device we are aware of. Models of the hydrostatic gas bearings have been developed and improved during the CTA program and verified with experimentation.



Three-dimensional gray-scaled compressor with variable etch depth. Note inner blade height variation.

PROJECT LEADERS

Mr. C. Michael Waits, ARL

Professor Alan Epstein, Massachusetts Institute of Technology

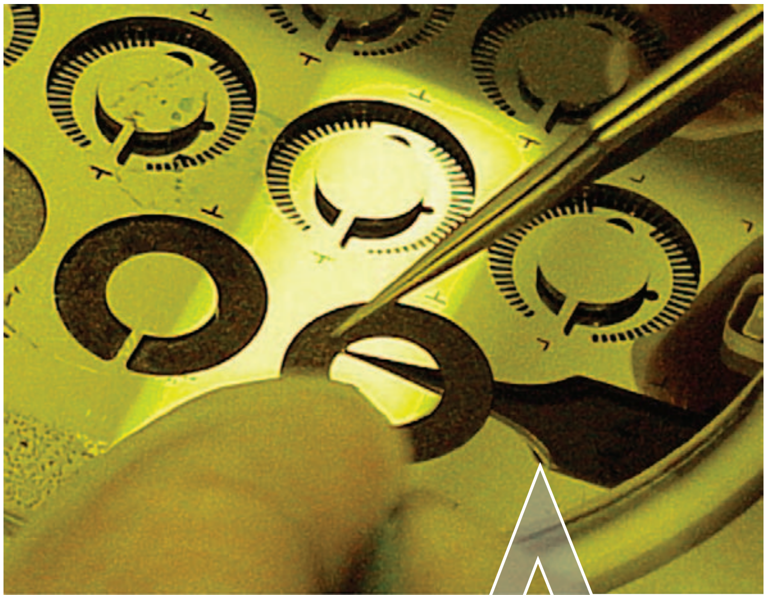
Professor Reza Ghodssi, University of Maryland

A MEMS turbocharger was developed as a test vehicle for both rotordynamics and turbomachinery. This six-layer device is similar in geometry and process to our MEMS gas turbine engine. We spun a MEMS turbocharger with an 8 mm diameter silicon rotor to 480,000 rpm (200 m/s), about 2/3 of the gas turbine engine design speed. Speed was limited by structural and rotordynamic issues that we now believe are resolved. The measured turbocharger aerodynamic performance is consistent with our design models.

Traditional MEMS fabrication processes produce structures that are two-dimensional projections of the shapes imaged on the wafer surface. This process does not allow for complex variation in the etch depth across a wafer, limiting engine geometry, which impacts engine performance. We developed a revolutionary gray-scale process technology that allows for arbitrary etch depth variation across a wafer, greatly extending the design space for Power MEMS. This technology will significantly improve turbomachinery performance at the microscale.

The high speed hydrostatic bearings developed in this program require high precision. With CTA funding, we are now the world leader in high aspect ratio precision deep etching in silicon, achieving bearing on the order of 20 microns with a tolerance of 0.75 microns over an etch depth of 300–400 microns. We are also a world leader in silicon wafer fusion bonding, having demonstrated bonded wafer stacks of up to 10 wafers, which is required for our gas turbine engine design.

Catalyst insertion into combustion chambers, done at the wafer scale.



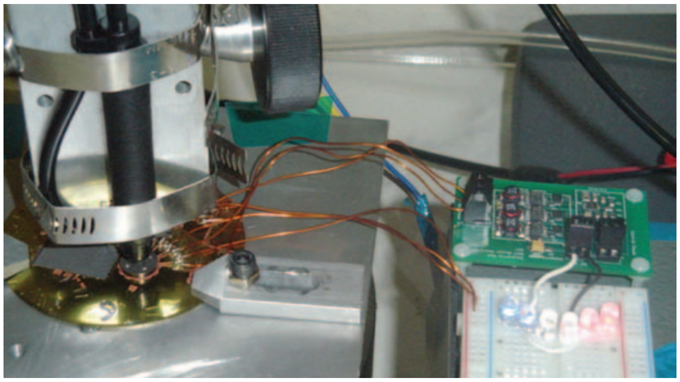
POWER AND ENERGY

MEMS MAGNETIC GENERATOR

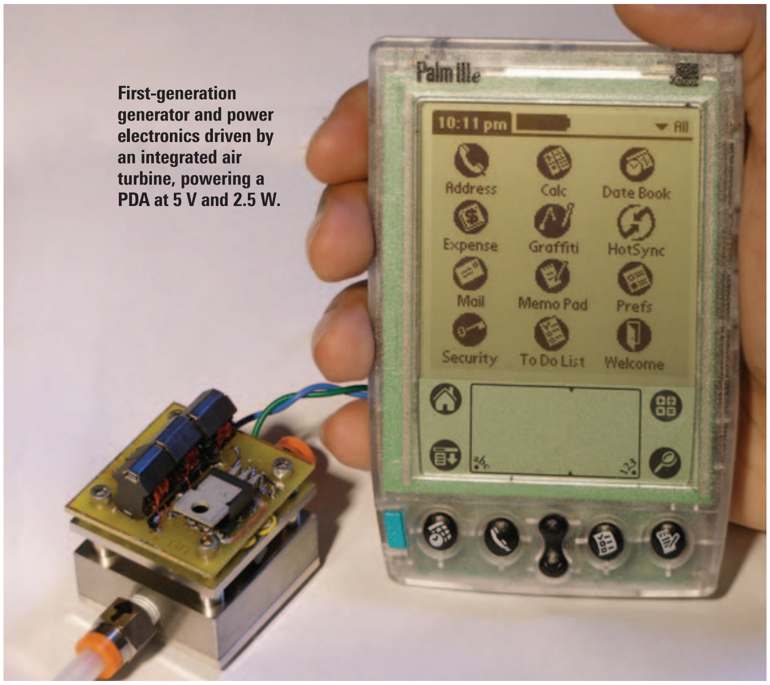
DESCRIPTION

Small-scale permanent-magnet synchronous motors and generators are under development. These machines, operating at or above the multi-watt power level, will be fabricated from bonded stacks of silicon wafers using standard MEMS silicon processing, and electroplating of integrated magnetic materials and thick conductors. By scaling their size down to the centimeter range, these machines can operate with current densities nearly 100 times larger than those of conventional machines. The large current densities result in power densities above 10^7 W/m^3 with a power output near 10 watts (W), an approximate 10-fold improvement in power density over conventional machines. When operated as motors, the machines could serve as coolant or fuel pumps, or air handlers. When run as generators, the machines could serve as electric power sources for Soldiers, autonomous sensors or robots.

The magnetic generators described here are specifically designed to be integrated with the MEMS gas turbine engine discussed in the next section. Their size, shape and operating speed match the gas turbine, and they generally share the same materials and fabrication processes. Further, special attention has been paid to the thermal design of the gas turbines to permit the use of the requisite magnetic materials at suitably low temperatures.



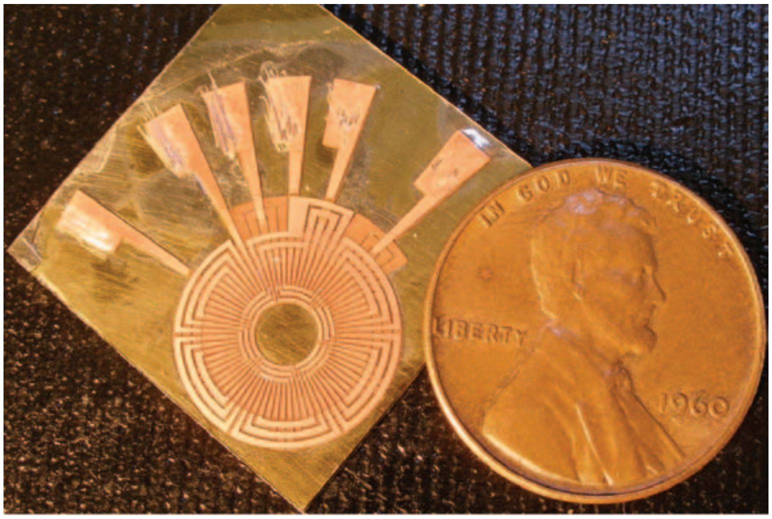
Second-generation generator and power electronics driven by an external air turbine, powering a bank of LEDs.



First-generation generator and power electronics driven by an integrated air turbine, powering a PDA at 5 V and 2.5 W.

ACCOMPLISHMENTS

The primary accomplishment of this project is the development and demonstration of high-power-density magnetic motors and generators that operate in the 10 W range. These machines have been demonstrated primarily as generators. For example, the figure at bottom left shows a first-generation generator with its power electronics powering a personal digital assistant (PDA). The generator itself, and the conventional air turbine that drives it, are not visible inside the package; the power electronics located above, however, are visible. The turbine and generator operate near 200,000 rpm. The electrical power that they produce is conditioned by the power electronics and delivered to the PDA at 5 V and approximately 2.5 W with a pneumatic-to-electrical efficiency in excess of 40 percent. The figure above shows the operation of a second-generation generator with its power electronics lighting a bank of LEDs. This system has generated nearly 10 W of useful power at 350,000 rpm with an efficiency in excess of 50 percent. The figures on the next page show a close-up view of the electroplated stator, and a close-up view of the permanent-magnet rotor and its magnetization pattern as observed with magnetic viewing paper.



Electroplated stator from the second-generation generator.

Underlying the successful demonstrations of the generator systems described above are a variety of multi-disciplinary technological advances. Models of the mechanical, electromechanical, thermal and electrical behavior of the permanent-magnet synchronous generator systems have all been developed, experimentally verified and used for the purposes of optimized design. Mechanical and magnetic material properties have been measured, at elevated temperatures where necessary, to support the modeling and design efforts.

Electroplating fabrication processes for high-aspect-ratio and high-density laminated magnetic cores and multi-layered windings have been developed. It is with these fabrication processes that the windings and cores can be integrated into the silicon structure that is the generator body. The models in turn reflect the capabilities of these fabrication processes.

Power electronics specifically tailored to the characteristics of the generator have been designed and demonstrated. Finally, air bearings capable of supporting the relatively heavy rotors of the magnetic generator have been redesigned based on a newly established micro-gas bearing theory and past experience in successfully spinning silicon-based micro turbines at rotor tip speeds near 370 m/s. The fabrication and testing of heavy rotor bearing test devices are underway and, when successful, will form a first-of-its-kind demonstration of supercritical, high-speed operation of multi-layer compound rotors necessary to enable MEMS based magnetic generators. Finally, also as part of this project, power electronics and optimal control algorithms have been devised to operate the turbine generator while charging advanced batteries. Such controls will be most useful for Soldier systems.

PROJECT LEADERS

Mr. C. Michael Waits, ARL

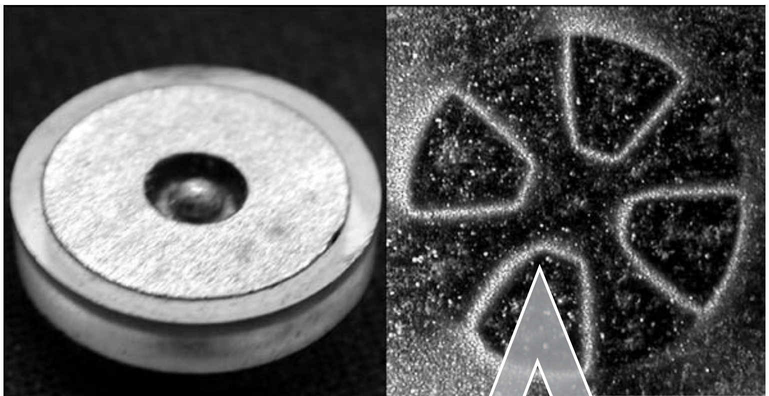
Professor Mark Allen, Georgia Institute of Technology

Professor David Veazie, Clark Atlanta University

Professor Jeffrey Lang, Massachusetts Institute of Technology

Professor Brad Lehman, Northeastern University

Permanent-magnet rotor from the second-generation generator (left) and its magnetization pattern as observed with magnetic viewing paper (right).



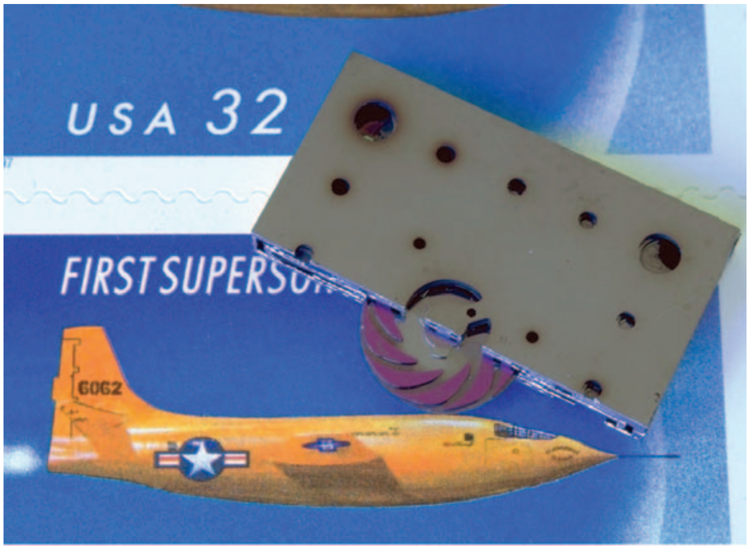
POWER AND ENERGY

MEMS GAS TURBINE ENGINE

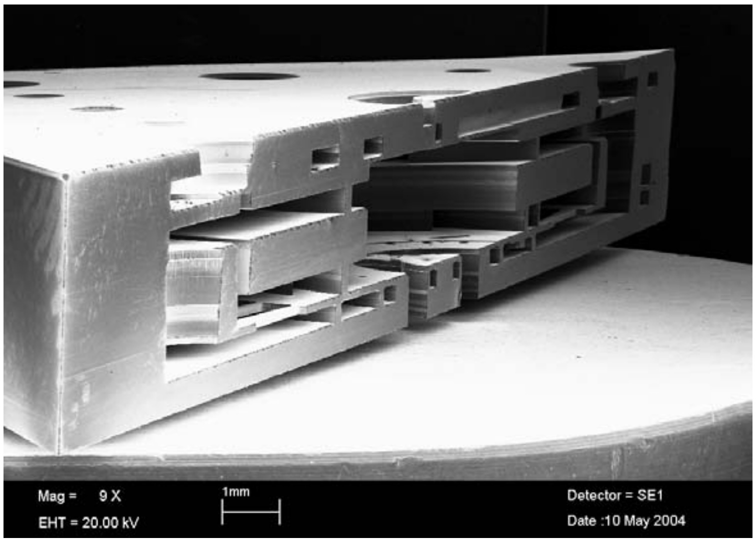
DESCRIPTION

A MEMS gas turbine generator is under development for portable power applications. For the Soldier, this device will serve as a battery replacement providing 10 to 20 W of electric power from a 5 cubic centimeter engine with a mass of about 10 grams (excluding fuel and fuel tank). While the efficiency of this engine is constrained by its size and fabrication capabilities, its performance relative to batteries will still be impressive. The MEMS gas turbine generator system (including fuel and fuel tank) will weigh five to ten times less than current batteries when sized to provide an equivalent amount of energy. This weight reduction is possible because the gas turbine is a fueled system, benefiting from the high energy content of hydrocarbon fuels. This device will significantly reduce the load carried by Soldiers.

We are currently building a MEMS gas turbine engine and a MEMS electric generator (discussed in the previous section). To reduce complexity and risk, the current version of the engine does not include an electric generator, although its design allows for later integration. This engine will showcase the feasibility of MEMS gas turbines by demonstrating self-sustaining operation (a major milestone for all gas turbine engine programs).



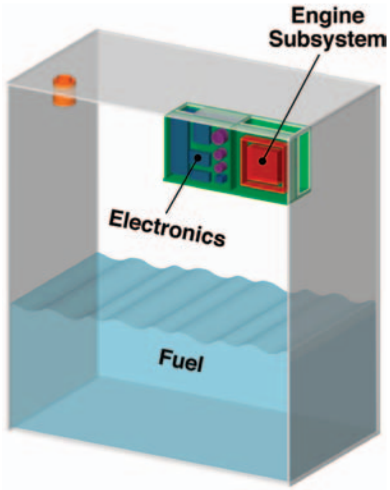
MEMS gas turbine engine prototype.



Cross-Section through a 9-layer MEMS gas turbine engine prototype.

ACCOMPLISHMENTS

Models developed and verified as part of the MEMS components program were combined into an overall engine system model. The system model integrates the couplings between the different subsystems, which is critical for an accurate representation of the overall system performance. The model highlighted issues related to the MEMS gas turbine that are atypical of gas turbine systems. For instance, in a typical gas turbine as speed increases, turbine power outpaces compressor power and viscous loss, so that net power also increases. However, in a MEMS gas turbine with lower efficiency turbomachinery (due to fabrication constraints and scale) and limited thermal isolation, as speed increases, compressor power can outpace turbine power because increases in viscous loss result in substantial increases in heat transfer to the compressor that detrimentally impact compressor performance. Thus increased speed does not necessarily increase net power in the MEMS gas turbine. The model was used to explore engine operational characteristics. Optimization runs were performed on the resulting model aimed at both maximizing net power and minimizing fabrication complexity. The resulting design is consistent with fabrication capabilities and self-sustaining operation.



Array of compressors on a wafer demonstrating the batch fabrication nature of MEMS.

The MEMS gas turbine engine is arguably the most complex MEMS device ever built. To manage programmatic risk, our development philosophy for successive generations of devices is one of evolution, minimizing the number of new process steps required in new devices. The engine contains only two major differences from the successful turbocharger device described in the components section of this report. The first difference is an additional layer in the rotor consisting of a small diameter shaft to increase the thermal isolation in the rotor between the compressor and turbine, because compressor performance is severely reduced by heat transfer from the turbine. Short loop process tests have demonstrated this technology.

The second difference is placing the compressor and turbine blades on separate wafer levels from their supporting disks. This process produces uniform height blades that substantially reduce the imbalance level in the rotor, which is necessary for stable high speed rotation. The cost is an increased number of wafers and bonds required, which increases complexity. This process technology has been successfully demonstrated in a build of a high-speed MEMS bearing test device.

The design model and fab process results were incorporated into an overall engine design consisting of ten wafer levels. The design has been translated into photolithography masks, which are used by our in-house microfabrication facility to lay out the engine patterns on silicon wafers. A set of 28 photolithography masks were drawn and fabricated. We plan to have the first-ever MEMS gas turbine engine to test in the spring of 2007 and demonstrate self-sustaining operation by the end of this program.

PROJECT LEADERS

Mr. C. Michael Waits, ARL

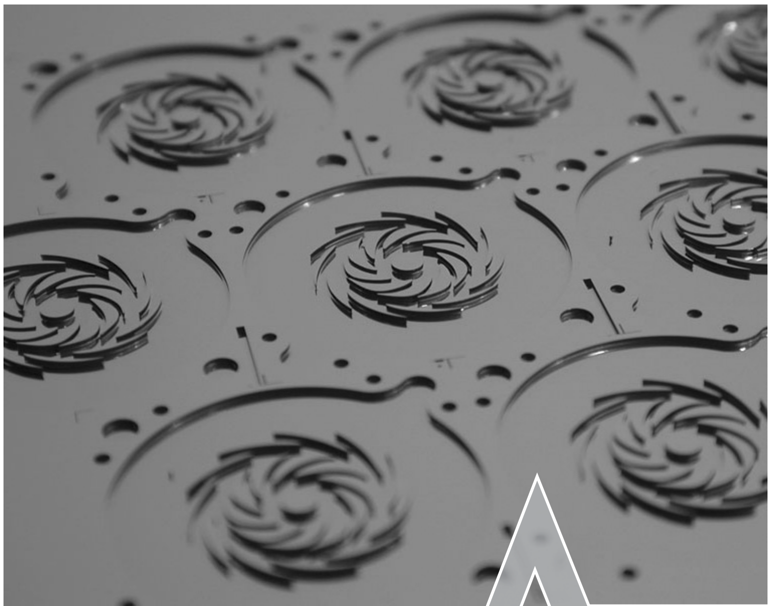
Professor Alan Epstein, Massachusetts Institute of Technology

Professor David Veazie, Clark Atlanta University

Professor Mark Allen, Georgia Institute of Technology

Professor Reza Ghodssi, University of Maryland

Engine packaged with fuel. Due its very high power density, the MEMS engine volume is negligible relative to the fuel volume.



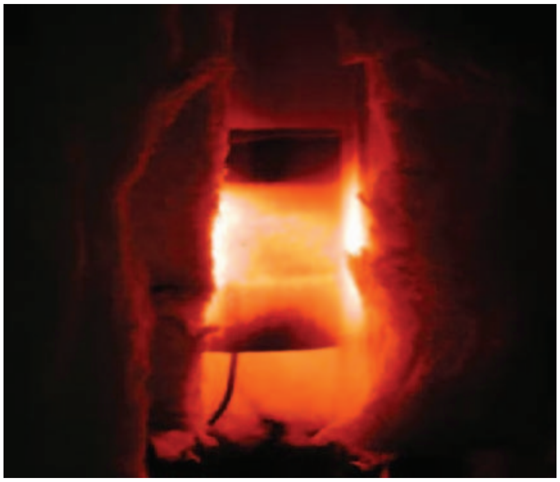
POWER AND ENERGY

SOLID OXIDE FUEL CELLS/LIQUID FUEL REFORMATION

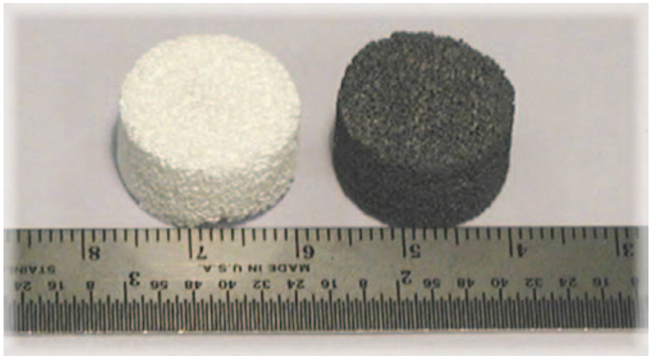
DESCRIPTION

The research supports the development of small, high-performance, lightweight, compact SOFC power systems operating on logistic fuels (JP-8, diesel). These will provide 100–10,000 watts. SOFCs cannot directly oxidize large, complicated molecules in logistic fuels. Advanced catalysts, supports, and materials are being developed to convert large molecules into fuels that can be directly oxidized. These catalysts, materials, and supports are used in catalytic partial oxidation (CPOX) reforming to syngas (H2 and CO) and partial reforming to produce high concentrations of C2–C4 hydrocarbons.

The research develops regenerable, stable sorbents that can efficiently remove hydrogen sulfide (H2S) to < 1 ppm levels from hot reformate gas mixtures produced by the partial oxidation. This involves the development and evaluation of advanced sorbent compositions to be used at high temperatures where the commercial sorbents fail to meet the need. The sorbent should be able to operate at the same high temperature (650-800 degrees Celsius) as the SOFC to avoid complexity. We have identified mixtures of rare earth oxides suitable as high-temperature sulfur sorbents. We have developed a new technology to allow regenerative use of these sorbents at high temperatures with minimal impact on the fuel cell system characteristics.



Working rhodium catalyst in a reactor that converts logistic fuels to fuels directly compatible with solid oxide fuel cells.



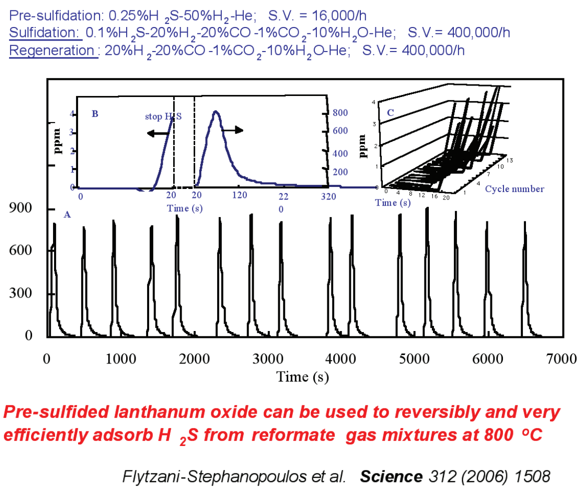
Ceramic support (left) and ceramic support covered with rhodium metal catalyst (right). This supported catalyst aids in converting logistic fuels to fuels directly compatible with solid oxide fuel cells.

ACCOMPLISHMENTS

The team built and operated an experimental system to study the conversion of logistics fuels to fuels compatible with SOFCs. This system was tested with several logistic fuels. Operating parameters that lead to high conversions to desired products have been determined. These parameters and tests will provide the basis for designing and building small, compact, high performance SOFC power systems.The team demonstrated that additives such as aromatics and sulfur can be managed in reforming for SOFCs. They determined the limits in the concentrations of these components and demonstrated how activity was affected and how deactivated systems can be reactivated.

The team demonstrated that production of SOFC-compatible fuel from logistic fuels can be rapidly started-up within several seconds. Rapid start-up will allow the power production from these devices to satisfy the varying power needs.

The desulfurization work has led to major development and breakthrough technology. We have developed novel sorbent materials which reversibly adsorb hydrogen sulphide (H2S) from a reformate gas mixture before the gas passes over a fuel cell's anode. These adsorbents, based on lanthanum and cerium oxides, can work



Cyclic sulfidation/regeneration of pre-sulfided La2O3.

efficiently to remove H2S to sub-ppm levels over a temperature window of 400-800 degrees Celsius.

We have designed a small reactor where H2S adsorption and sorbent regeneration take place, so that only cleaned fuel enters the fuel cell. The adsorption reaction happens in less than one millisecond. Thus, very short contact times can be used in the sorber unit. This translates into a small desulfurization reactor for practical application to power generators. Any regeneration gas mixture, including unused gas from the fuel cell, can be used to sweep this adsorbed H2S from the saturated sorbent surface very quickly.

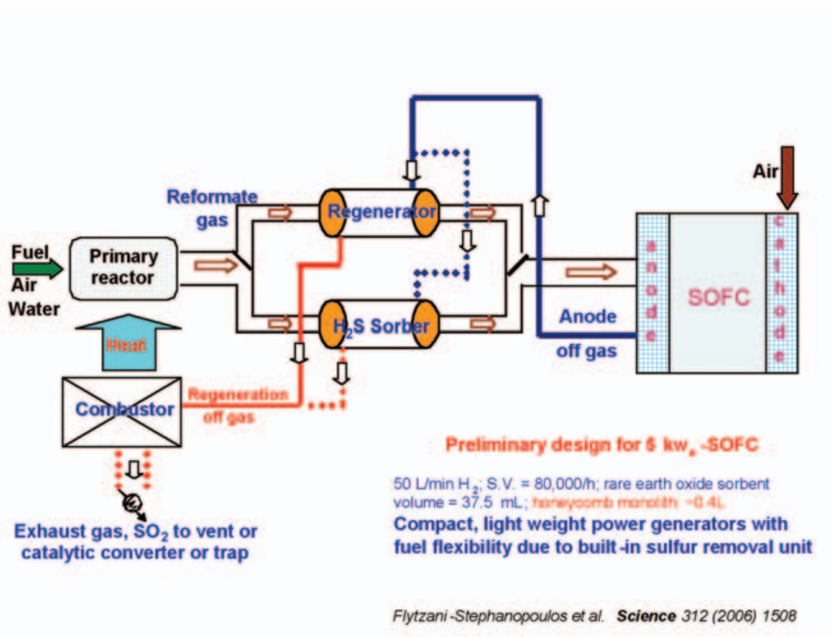
Protecting fuel cells from sulfur impurities is a major problem. While methods such as removal of sulfur from a liquid fuel before using have been proposed, this removal may not be complete. In some of its field operations the Army may have to work with heavy fuels (JP-8, diesel) containing sulfur. Our technology provides a solution. A small dual-bed sorber/regenerator containing our sorbent material can be installed upstream of the fuel cell anode to totally remove sulfur. The sorber can operate at the same temperature as the SOFC or at lower temperatures. The added weight or volume is very small, less than 1L/5 kWe. Our technology frees the SOFC from having to work with natural gas or sulfur-free fuels.

PROJECT LEADERS

Professor Maria Flytzani-Stephanopoulos,
Tufts University

Professor Lanny Schmidt, University of Minnesota

Dr. Deryn Chu, ARL

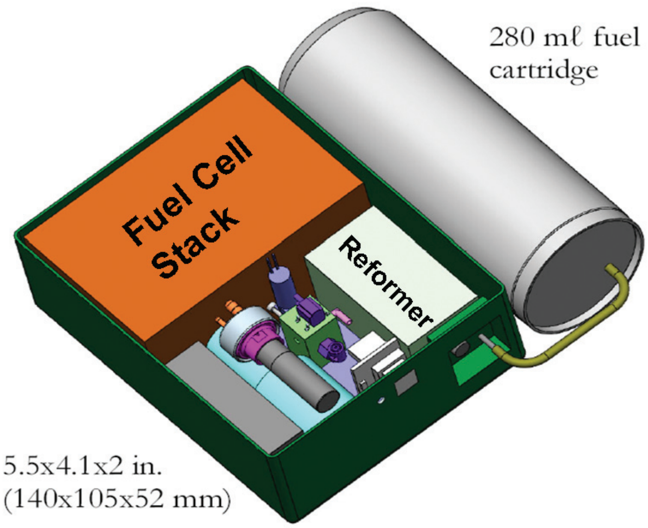


On-board sorbent sulfidation/regeneration for SOFC.

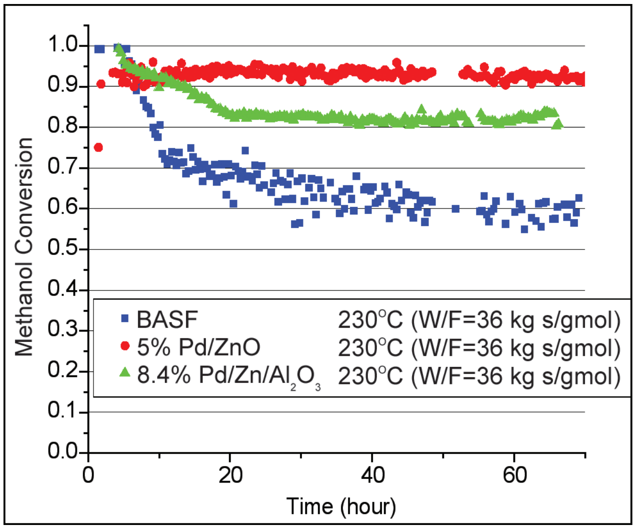
HYDROGEN GENERATION FOR FUEL CELLS VIA METHANOL STEAM REFORMING

DESCRIPTION

We have developed micro-reactor technology for hydrogen generation from methanol liquid fuel. The hydrogen generated here can be used to produce electric power for Soldier power applications. Methanol is an ideal fuel for generating hydrogen on board to power mobile devices such as laptops or cell phones. Our technology is directed at a 20W methanol powered power source that includes a methanol reformer, fuel cell, combustor and a power conditioner, in a compact package. To serve as a replacement for batteries, we must be able to operate at low temperatures and produce minimal amounts of carbon monoxide (CO), a poison for fuel cell catalysts. The catalyst is wall coated within microchannels to achieve high rates of heat transfer and high volumetric efficiency for hydrogen generation. The catalyst is based on Pd-Zn/Al_2O_3 to maximize catalyst performance and selectivity. The fuel processor will be part of a complete system similar to that shown here below that includes a fuel cartridge, reformer, combustor and a fuel cell stack.



Conceptual design of a reformed fuel cell power system.

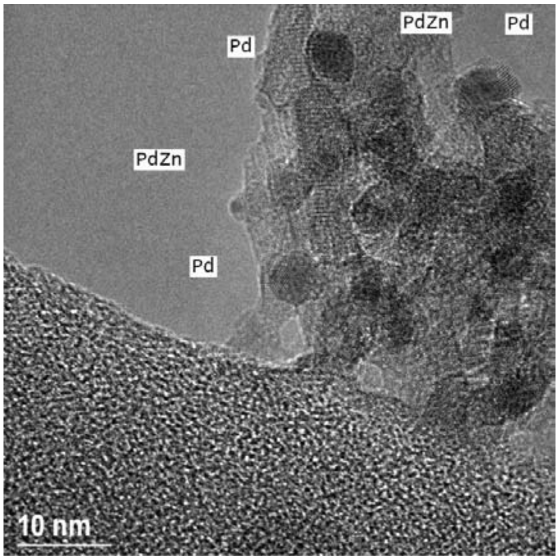


Methanol conversion as function of time for the UNM catalyst compared with the commercial catalyst.

ACCOMPLISHMENTS

This catalyst is more stable than the commercially available Cu/ZnO/Al_2O_3 catalyst. The figure above shows a comparison of the performance of UNM developed catalysts with the commercially available catalyst. Our catalyst consists of Palladium (Pd) supported on Zinc Oxide (ZnO) and PdZn alloy nanoparticles supported on an alumina support. The alumina provides improved activity and stability to the catalyst. The Zn is necessary to achieve low selectivity to CO. As shown above, the catalyst shows considerably higher stability compared with the commercially available catalyst. The BASF catalyst shows rapid decline in activity, while both the Pd/ZnO and Pd/ZnO/Al_2O_3 provide more stable operation. Although the Pd/ZnO shows the highest stability, the Pd/Zn/Al_2O_3 shows higher productivity than Pd/ZnO as seen from the W/F ratio. When these ratios are compared, it can be seen that the Pd/ZnO requires approximately three times the catalyst to achieve comparable activity to the Pd/ZnO/Al_2O_3 catalyst.

The internal microstructure of our developed catalyst is shown on page 93. It can be seen to consist of particles less than 10 nm in diameter located on the alumina support. We have found that the particles of this size



High resolution transmission electron micrograph of the UNM Pd-Zn/Al_2O_3 catalyst showing the presence of Pd and PdZn alloy nanoparticles.

range are very stable and provide long term activity and selectivity. While it is important to form the Pd-Zn alloy, we find that it is equally important to disperse the ZnO on alumina first, before depositing the Pd phase. The dispersed ZnO cannot be seen in this image since it is spread as a very thin layer on the alumina support.

We have also developed a method for coating microchannels with catalyst using the gas displacement method. This method yields adherent catalyst wall coatings of 25 micron thickness that are suitable for developing microchannel reactors. The image to the right shows an example of a microchannel with a 25 micron porous catalytic coating. Our technology will make it possible to construct compact devices to convert methanol water mixtures into hydrogen for generating Soldier power for mobile applications. Incorporating the catalyst via a coating technique will drastically lower the overall pressure drop across the microreactor when compared to a packed bed reactor. This results in a lower balance-of-plant for the fuel cell and reformer system, thus increasing the overall power output of the system. The overall system power density is much greater than batteries, reducing the weight that a Soldier needs to carry. The mobile power sources based on methanol fuel cells will be of considerable benefit for powering laptops and cell phones where electricity is not available.

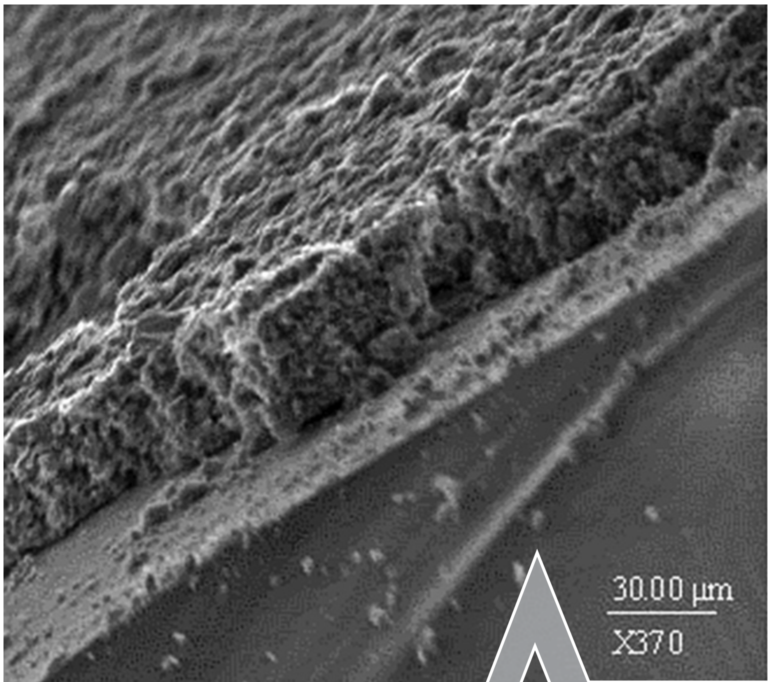
PROJECT LEADERS

Dr. Deryn Chu, ARL

Abhaya K. Datye, University of New Mexico

Mr Steve Samms, Mr. Steve Rogers, and
Mr Jerry Hallmark, Motorola Labs

Scanning Electron Micrograph of a microchannel surface coated with methanol reforming catalyst.



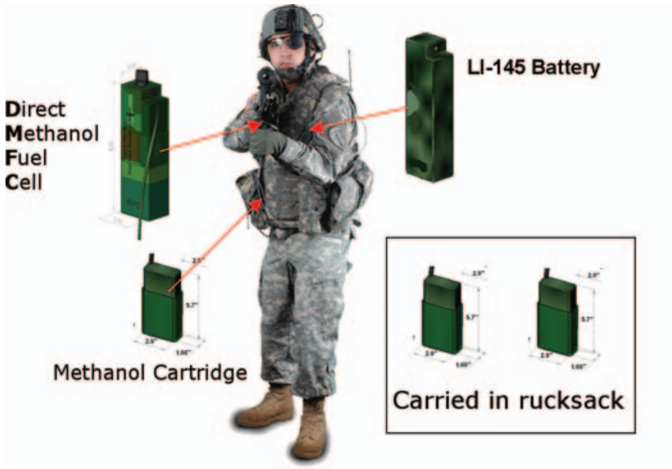
DIRECT METHANOL FUEL CELLS

DESCRIPTION

Direct Methanol Fuel Cell (DMFC) technology offers a pathway to lowering the weight carried by the Soldier by providing a more energy dense power supply than is capable with batteries.

The DMFC program within the Power & Energy CTA is focused on developing more active and more durable methanol oxidation catalysts and membrane electrode assemblies. Success in these areas results in smaller, lighter systems and more electrical energy per kilogram of fuel.

The fruits of this CTA program feed directly into the Defense Acquisition Challenge Program developing the M25 Soldier Power System. This hybrid DMFC/Lithium Battery system will reduce the 72-hour mission weight of the Soldier by 10 to 15 pounds.

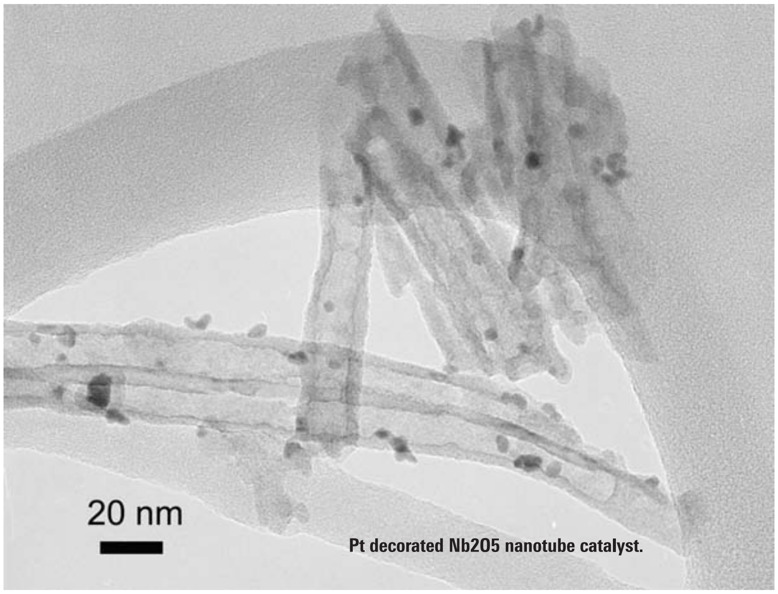


M25 Soldier power system.

ACCOMPLISHMENTS

The improved methanol oxidation catalyst discovery work was divided into four technology pathways: modeling, novel support materials, novel catalyst structures and development of improved membrane electrode assemblies.

Work focused on modeling the activation energy for methanol oxidation and developing experimental data to support the model which predicted that a sequentially deposited Platinum Ruthenium (PtRu) nanocluster would be a more active anode catalyst than the current PtRu alloy. The experimental group successfully fabricated the catalyst structure suggested thereby. A new model was developed to help predict the best structure for the Pt on Ru catalyst.

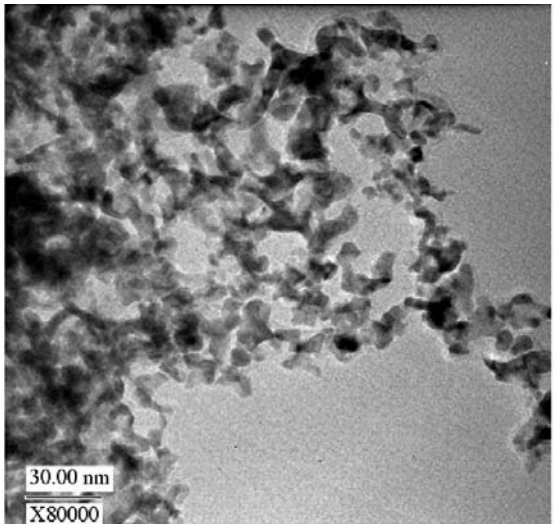


Pt decorated Nb2O5 nanotube catalyst.

Additional efforts focused on developing novel catalyst support materials to enhance catalyst activity and durability. Catalyst support materials must have high surface area, electrical conductivity and high durability, a rare combination of properties. A range of substrate materials were created and tested to find candidates meeting the catalyst support criteria. Conductive nanotubes of Niobium Oxide (Nb_2O_5) meeting the criteria were fabricated. The Nb_2O_5 substrate was successfully used to make a Pt catalyst as a validation step.

Further efforts focused on developing higher activity catalysts by creating nano-scale engineered structures. Pt-Ru nano-wire networks were successfully fabricated. The methanol oxidation activity of this material was substantially higher current catalysts.

Other work focused on novel, highly active catalyst structures and catalyst modifications to enhance durability. A novel, highly active catalyst was made by decorating



Engineered PtRu nanocomposite DMFC Catalyst.

PROJECT LEADERS

Dr. Deryn Chu, ARL

Dr. Radoslav Adzic, Brookhaven National Lab

Dr. David Reichert, DuPont Fuel Cells

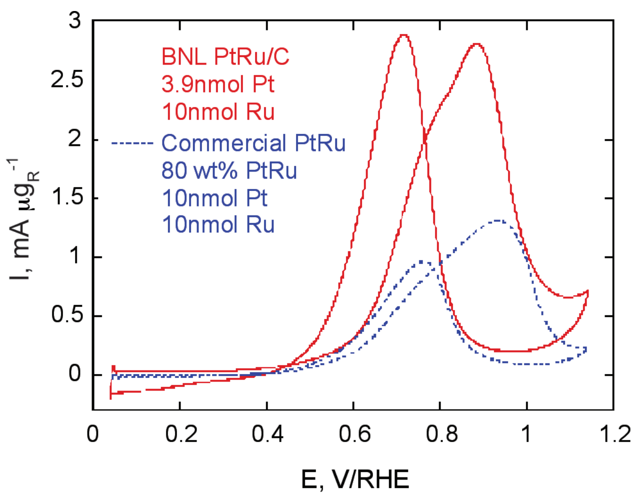
Dr. Thomas Mallouk, Pennsylvania State University

Dr. Carlos Cabrera, University of Puerto Rico

Dr. Plamen Atanassov, University of New Mexico

a Ru core with Pt; the inverse of the typical approach. The new "PtMRu" catalyst showed a mass activity level 2.5 times higher than current methanol catalyst. A second successful catalyst candidate was made. The new Pt/NbOx catalyst shows methanol oxidation activity without the need for Ru and this may be a much more stable catalyst.

Additional efforts focused on identifying the most active catalyst available and creating a stable, high performance membrane electrode assembly for use. The Gen IV MEA was scaled up from proof of concept to a high volume capable process. The Gen IV DMFC MEA increased the durability by a factor of 10. Systems using this technology have run for over 5000 hours. A new anode catalyst with higher activity than the current used in commercial Gen IV MEAs was identified. An electrode structure using this new catalyst was developed that generates higher power density per gram of catalyst. Developed a method to get in-situ DMFC data from significantly smaller samples of experimental catalyst enabling faster transition from new catalyst discovery to an enhanced.



High activity Pt monolayer on Ru methanol catalyst.

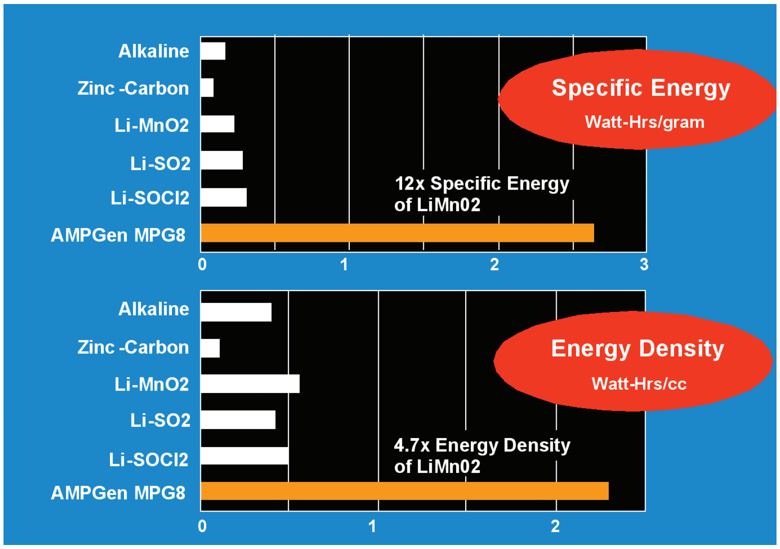
POWER AND ENERGY

METAL HYDRIDE FUEL CELLS

DESCRIPTION

We have developed a fuel cell electric power generation technology with very high specific energy and energy density called Advanced Micro Power Generators (AMPGEN). The technology is based on Proton Exchange Membrane (PEM) hydrogen-oxygen fuel cells. The fuel cells integrate together a novel passively regulated metal hydride hydrogen generator with the PEM fuel cell stack. The fuel cell generator technology is scalable to accommodate a wide range of size, shape, energy and power requirements from 1 mW to Watts.

The development of the AMPGen fuel cells started in 2002 with a DARPA-MTO Contract with Honeywell. That program Honeywell demonstrated 1, 3 and 10 mW fuel cell generators with very high specific energy of 2600 Whr/kg and energy density of 2200 Whr/L; many times higher than that of batteries. The current effort has a goal of demonstrating a greater than 100 mW fuel cell. This fuel cell will be demonstrated in the Omnisense® Unattended Ground Sensor (UGS) system by McQ Co. at ARL. The success of this program will demonstrate the potential of the AMPGen fuel cells for higher power, lower weight and extended mission life in applications such as UGS, Unmanned Aerial Vehicles (UAVs), and warrior carried power.



Specific energy and energy Density comparisons of AMPGen fuel cells and primary battery technologies.

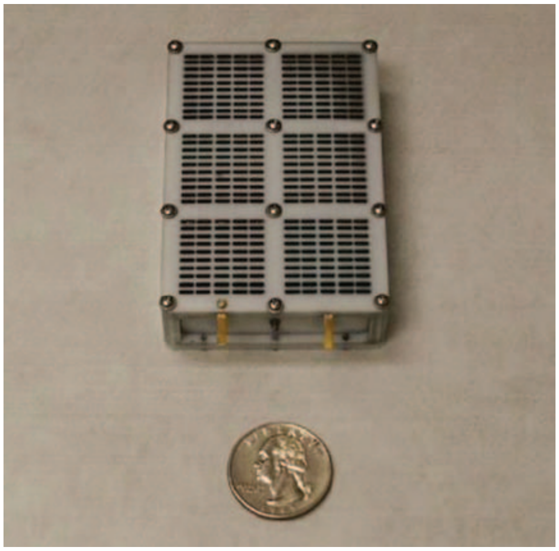
Early AMPGen fuel cell generator prototypes. These prototypes were 30 mW (3V @ 10mA) devices.

ACCOMPLISHMENTS

The metal hydride fuel cell development goal was to build on the success of the DARPA and Honeywell funded development effort by scaling up the AMPGen micro power generator to demonstrate a power source with a 100 mW or higher power. These devices would be delivered for testing and evaluation. The fuel cells will be demonstrated in the field by powering the Omnisense® UGS system for a period of time.

In September 2006, Honeywell delivered three of the redesigned and scaled prototype fuel cells to ARL. Honeywell also designed, built, and delivered three hybrid circuits which interface the fuel cells to the UGS system. The new design of the prototype fuel cell is shown in the figure. The design was changed to a rectangular shape to give increased PEM cell surface area for increased power output, and to make more efficient use of space in a system. The fuel cell is about the size of a deck of cards. The fuel cell has six cells in series operating at 0.6 to 0.8 volts each to give an output voltage of 3.6 to 4.8 volts at 20°C. It is 1.4 times the volume but still lighter at 0.65 times the weight of a D cell and the energy capacity is 5 times higher.

The delivered AMPGen fuel cells were designed to operate at a minimum of 100 mW under worst case conditions at -20 °C. The prototype fuel cells are rated at a minimum of 100 mW over a temperature range of -20°C to 60°C, and a humidity range of 10 to 90 percent Rh. Significantly higher power levels are possible over



AMPGen fuel cell generator delivered to the Army. Fuel cell has an output power of 250 mW, 4.8V @20 °C.

most of this temperature and humidity range. The current cells have a measured output of >250mW at 20°C. The fuel cells have an energy capacity of at least 150 Whr when fully loaded with the solid metal hydride fuel.

- Three AMPGen fuel cells were designed, fabricated and delivered to ARL with > 100 mW output power (250 mW at 20 ľC) for field testing in powering an UGS system.
- Three hybrid circuits were delivered to ARL to interface the cells with the UGS system.
- The PEM cell stack power density was increased by a factor of 3X and the cell efficiency was improved by almost 10 percent.

PROJECT LEADERS

Dr. Deryn Chu, ARL

Dr. Thomas Ohnstein, Honeywell

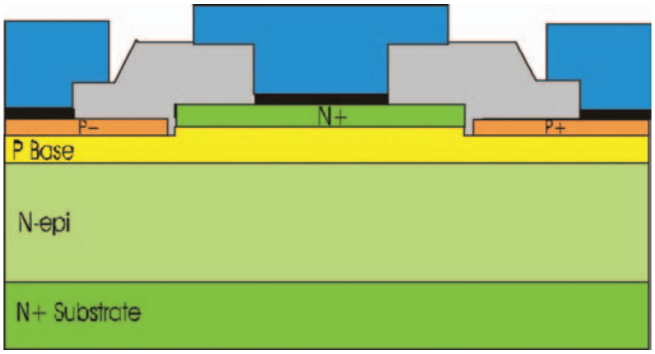
OmniSense® Unattended Ground Sensor System. This is the deployed version for US Army INSCOM. ***Photograph courtesy of McQ Inc.***

POWER AND ENERGY

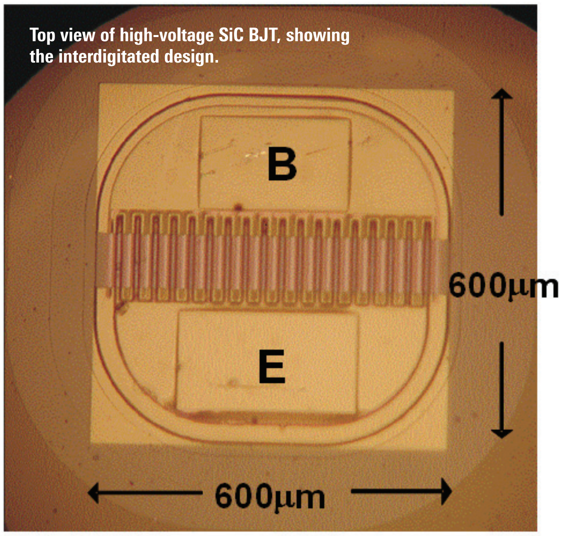
SILICON-CARBIDE DEVICES

DESCRIPTION

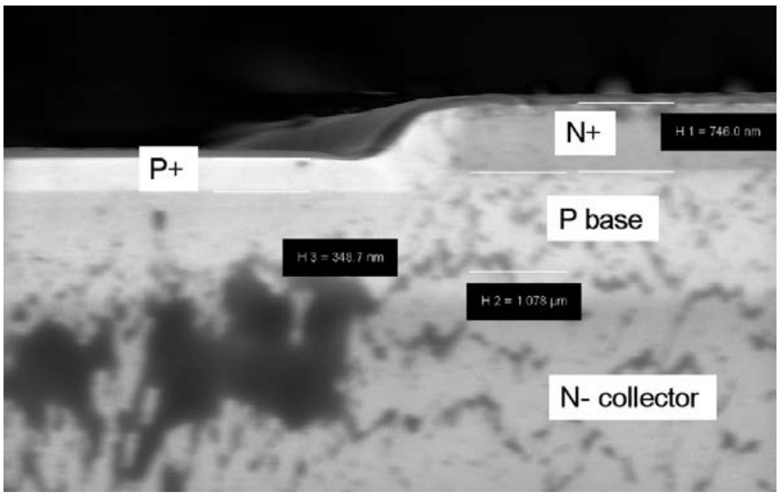
We have focused on the optimization of high-voltage SiC semiconductor devices, particularly Bipolar Junction Transistors (BJTs) for power switching applications. We have examined key device parameters such as current gain, specific on-resistance, breakdown voltage, switching (turn-on and turn-off) times and determined the trade-offs between current gain and specific on-resistance as well as between specific on-resistance and switching times.



Schematic cross-section of our novel high-voltage selectively base regrown SiC BJT.



Top view of high-voltage SiC BJT, showing the interdigitated design.



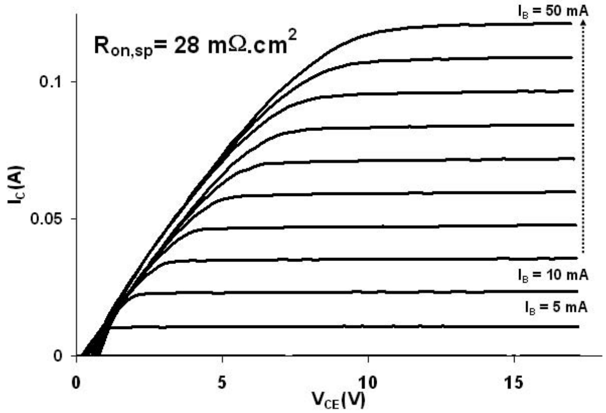
SEM cross-sectional view of the emitter and base regions of our novel high-voltage selectively base regrown SiC BJT.

ACCOMPLISHMENTS

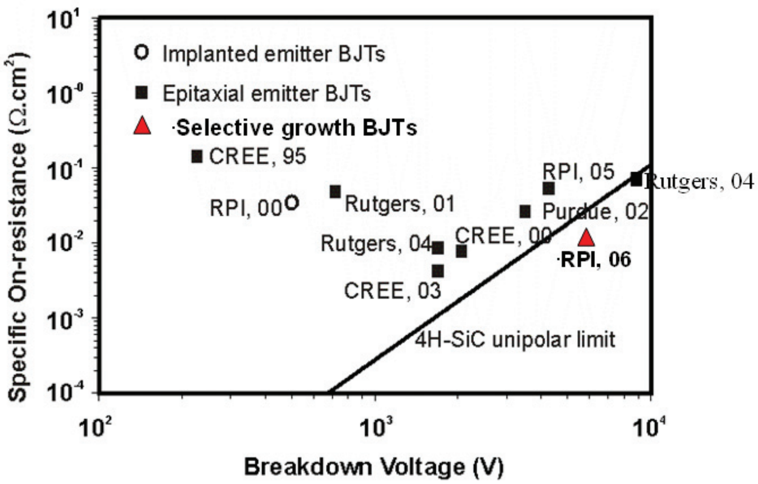
Using a selective base regrown process, which has been developed specifically for device demonstration, we are able to place heavily doped, epi-grown p+ base contact regions very close to the emitter regions, reducing the extrinsic base resistance and eliminating the lattice defects resulting from the implanted p+ base process. Also, by optimizing the termination process, we have substantially increased the breakdown voltage. In particular, we have achieved a specific on-resistance of 28m_-cm2 for a 6kV blocking 4H-SiC BJT. Compared to the state-of-art SiC BJTs, our specific on-resistance is significantly superior to them in forward drop performance.

Our team has also assessed the operational reliability of these SiC BJTs. First, we identified a degradation mechanism, which causes a rapid decrease in current gain during forward conduction. Then, we modified our integrated fabrication process and eliminated this degradation, resulting in highly stable devices, even after extended operation at elevated temperatures.

With the substantial decrease in specific on-resistance, the efficiency of power electronics systems utilizing these high-temperature capable SiC BJTs is significantly enhanced, thus resulting in a decrease in size, weight and mission range of power electronic systems, such as power supplies for information appliances (cell phones, PDAs and PCs) for Soldiers.



Output I-V characteristics of our novel SiC BJT, indicating a record low specific on-resistance.



Specific on-resistance vs. breakdown voltage of SiC BJTs reported in the literature.

PROJECT LEADERS

Dr. Paul Chow, Rensselaer Polytechnic Institute

Dr. James Richmond, Cree

Dr. Pat Lenahan, Penn State University

Dr. R.D. Vispute, University of Maryland

Dr. Ken Jones, ARL

POWER AND ENERGY

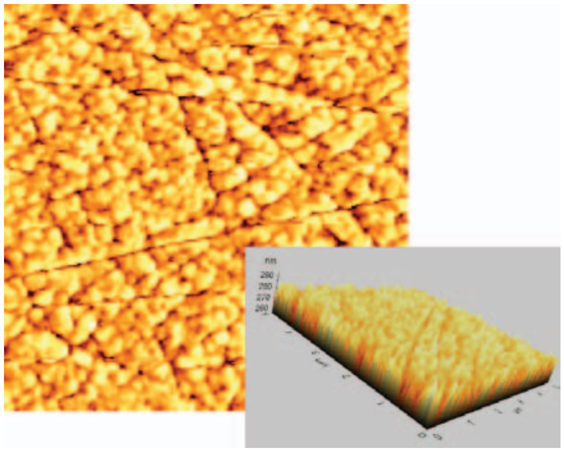
SILICON-CARBIDE MATERIALS

DESCRIPTION

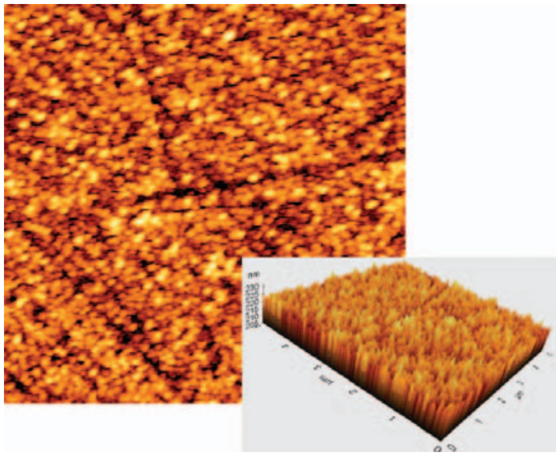
We are optimizating several key unit processing steps that are necessary for the fabrication and manufacturing of high-voltage SiC semiconductor devices. In particular, we are examining improved p-type implanation activation processes and Metal Oxide Semiconductor (MOS) processes in 4H-SiC. We are studying different capping layers, implantation or oxidation temperature, and post-implant activation or post-oxidation anneal temperatures.

ACCOMPLISHMENTS

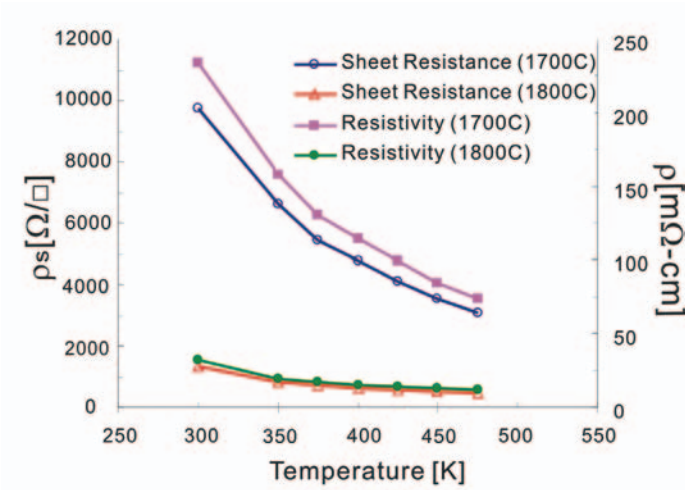
We have achieved one of the lowest sheet resistances in aluminum-implanted p-type regions and best ideality factor in pn junction diodes in 4H-SiC by using AlN and graphite as capping layers during the high-temperature activation annealing process. Also, we have studied different oxidation and post-oxidation ambients to achieve one of the lowest interface state densities and highest field-effect electron mobilities in 4H-SiC Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs). We have explored post-oxidation annealing in oxygen, NO, N2O and CO2 ambients. Furthermore, we are developing a physical understanding of the SiO2/4H-SiC interface and inventing new MOS processes. The structural properties of the SiO2/4H-SiC have been examined using Electron Spin Resonance (ESR) and a new 4H-SiC MOS process introduces positive oxide charges which can



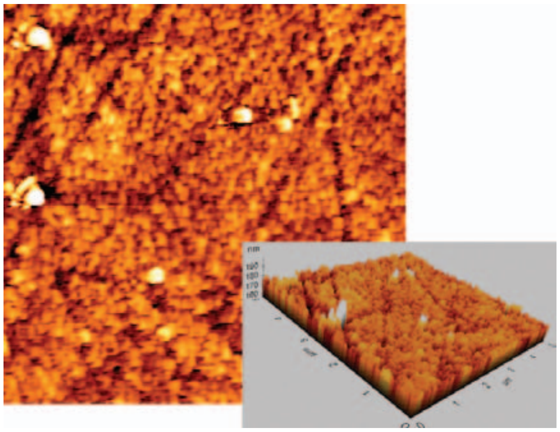
AFM pictures showing surface roughness
(a) bare sample before graphite cap and annealing.



(b) 1700 degree C annealed sample.



Sheet resistance and resistivity of implanted p-type layers after 1700 and 1800 degree C annealing.



(c) 1800 degree C annealed sample.

increase interfacial electron concentration with improved mobility due to reduced carrier scattering.

With the optimum device fabrication processes, high-performance SiC power devices can be manufactured reproducibly and a high functional yield and hence low cost. Subsequently, highly efficienct and reliable power electronics systems utilizing these high-temperature capable SiC device components result in a decrease in size, weight and mission range of power electronic systems, such as power supplies for information appliances (cell phones, PDAs and PCs) for Soldiers, in additional to system longevity.

PROJECT LEADERS

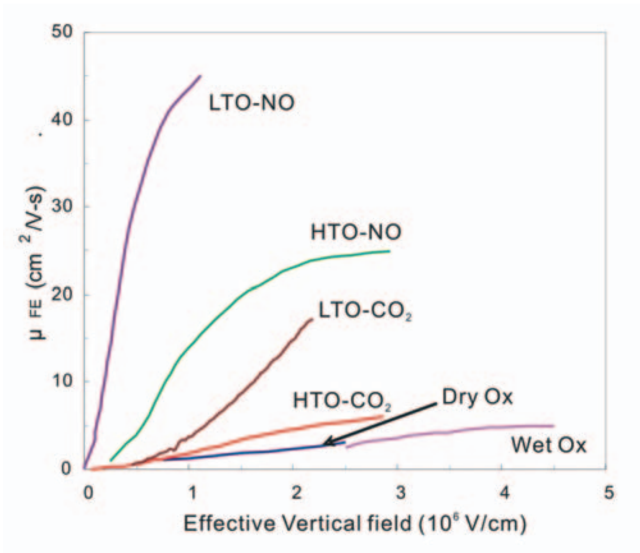
Dr. Paul Chow, Rensselaer Polytechnic Institute

Dr. James Richmond, Cree

Dr. Pat Lenahan, Penn State University

Dr. R.D. Vispute, University of Maryland

Dr. Ken Jones, ARL



Dependence of field-effect electron mobility on oxide deposition temperature and post-deposition anneal ambient treatment.

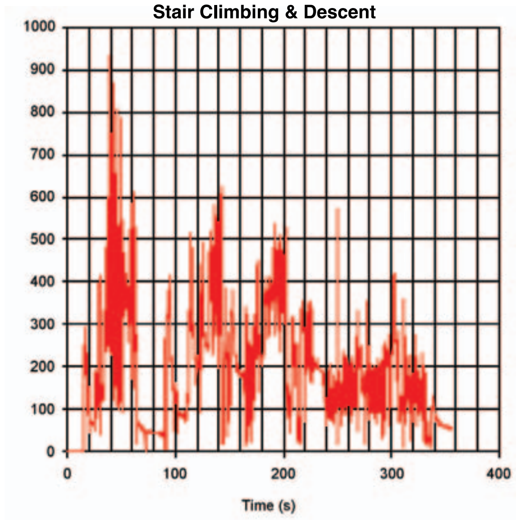
POWER AND ENERGY

ADVANCED POWER SOURCES FOR SMALL ROBOTIC VEHICLES

DESCRIPTION

The Army has identified the need for small, man-portable, autonomous robots that can perform close-in reconnaissance missions in confined spaces such as caves, tunnels, and buildings. While the specifications for such robots are evolving, some are already being used in the field. Desirable attributes for these vehicles include the ability to perform RSTA, portability, and autonomous stealth operation. Many of these attributes and mission requirements constrain the size and weight of the robot power source and dictate longer run-times.

Working within the P&E CTA, we have developed two new power sources providing significant improvement in energy and power densities. Although we have used iRobot, Inc.'s PackBot vehicle as the development platform, the approach is applicable to all small robotic vehicles. In addition, the power sources we developed have built-in diagnostic and prognostic capabilities, which will result in significant improvement in field maintenance of these systems. The first power source is based upon the secondary lithium-ion battery technology and was developed during Phase 1 of the CTA. The second power source, developed during the CTA Phase 2, is a hybrid design consisting of a lithium-ion battery and a Direct Methanol Fuel Cell (DMFC).



Typical load profile of a Small Robotic Vehicle.

The PackBot searches for booby traps on this truck on Najaf airfield.

ACCOMPLISHMENTS

To understand the small robotic vehicle power requirements, during the CTA Phase I, we performed extensive testing with three popular small robots: Talon, Urbot and PackBot. Many operational scenarios for these vehicles were used during this testing. The testing indicated that in comparison to stationary operation or coasting, significantly large amounts of power are needed during operations such as acceleration and stair climbing. For example, in case of the PackBot, while 100–400 watts of power is sufficient for most operations, peak power consumption for maneuvers such as stair and hill climbing could be as high as 900 watt.

The PackBot vehicle was selected as the power source development platform due to its extensive use in the Iraq and Afghanistan theaters. The power measurement results and the capability of the standard PackBot NiCad battery were considered in establishing the requirements for the power source. The key objective of the Phase I effort was to at least double the robot runtime while complying with the weight and the volume constraints defined by the existing PackBot NiCad battery. Next, leading energy storage technologies were reviewed and rechargeable lithium-ion technology was selected for the power source implementation. The key factors considered in this selection included energy and power densities, cycle life, calendar life, and technology maturity level. Ten lithium-ion power source prototypes were then

Hybrid Power Source Components

Li-ion Battery

Electronics

DMFC

developed and field tested. The new design, which is 25 percent lighter than the existing NiCad source, increased the PackBot run-time by approximately two and a half times. The goals we had set for the power source performance were thus exceeded.

In the second phase of the P&E CTA, we have developed a hybrid power source which consists of the previously developed lithium-ion battery and a 12 volt, 20 watt Direct Methanol Fuel Cell manufactured by Smart Fuel Cell GmbH. Ultra-low power electronics and a 92 percent DC to DC Converter are the other key elements of the hybrid source. The fuel cell has double the energy (440 watt-hours) than the battery while the battery can supply power levels up to 1000 watts. Together the battery and fuel cell thus provide an optimal power system for both low and high power needs.

In this system, the fuel cell replenishes the battery charge during vehicle use or power-off periods. The hybrid power source also supports low level vehicle loads. The charging feature of the system will significantly increase the mission length. In addition, the fuel cell, which provides charge to the battery, can itself be refueled with methanol in the field. The hybrid system is a smart system consisting of diagnostic and prognostic functions for both the fuel cell and the battery. These functions are very valuable for maintaining the power source in the shop or battle field environments.

PROJECT LEADERS

Dr. Ken Jones, ARL

Mr. Harmohan Singh, Honeywell

A Soldier from A Co., 326 Engineers, of the 101st Airborne Division working with PackBot in Najaf.

COLLABORATIVE TECHNOLOGY ALLIANCE

ROBOTICS

ROBOTICS CTA

OVERVIEW

OBJECTIVES

The Robotics Collaborative Technology Alliance (RCTA) is the Army's dedicated research team for developing unmanned vehicle technology for the Future Force. Funded and managed by the Army Research Laboratory (ARL), the RCTA provides advanced ground robotics research and technology for each of the armed services through the Office of the Secretary of Defense Joint Ground Robotics Enterprise (JGRE).

Robotics technology offers the Army new options for enhancing Soldier physical security and survivability, improving situational awareness and understanding, conducting transport, and carrying out reconnaissance, surveillance, targeting and acquisition missions in an era of rapidly evolving operational and technological challenges.


RCTA research envisions a time when robots will be seamlessly integrated into the battlespace as force multipliers.

TECHNICAL AREAS

The RCTA identifies and investigates critical gaps in the unmanned systems knowledge base in three technology areas:

Perception: Technologies that allow robotic vehicles to sense and understand their environment, especially obstacles that impair mobility or mission effectiveness.

Intelligent Control Architectures: Technologies that enable robotic systems to autonomously plan, execute, and monitor tasks while adapting to changes in complex, dynamic environments and ensure safe and secure movement.


RCTA perception technology enables an unmanned ground vehicle to autonomously navigate through cluttered stationary environments.

Human-Machine Interfaces: Technologies that allow Soldiers to effectively task and interact with multiple heterogeneous robotic systems while minimizing operator workload.

The RCTA also focuses on supporting Future Combat System (FCS) unmanned systems success with honed perception research to mitigate the risks of using robots in the cluttered and dynamic environments of urban operations.

ACCOMPLISHMENTS

The RCTA has made major performance gains in autonomous vehicle mobility and the planning and tactical behaviors solutions that pave the way for operational troops to effectively supervise and interact with teams of autonomous air and ground vehicles imbued with complex behaviors.

- RCTA-developed technology has been transitioned to the FCS Autonomous Navigation System program; TARDEC's Vetronics Technology Integration (VTI) program; DARPA's Organic Air Vehicle (OAV)-II program; AMRDEC/AATD's Unmanned Autonomous Collaborative Operations (UACO); and the Navy's Unmanned Surface Vehicle (USV) program, among others.

- Demonstrated real-time detection and tracking of humans and vehicles from a moving vehicle using several sensor modalities, including LADAR and video that will enable Unmanned Ground Vehicles (UGVs) to operate in small combat teams.

The RCTA has developed the foundational technology that will enable robots to engage in leader/follower operations.

- Developed processing algorithms for scene understanding and object identification that provide detailed, higher-level environment descriptions to tactical behaviors.

- Invented algorithms that enable the unmanned ground vehicle to anticipate, detect, and analyze conditions that may affect mobility performance, including: understanding the motion of other agents to safeguard the robot, other vehicles, and pedestrians; and anticipating conditions at long-enough range to enable early decisions.

- Developed intelligent control functional architecture allowing UGVs, Unmanned Air Vehicles (UAVs) and Unattended Ground Sensors (UGS) to be seamlessly integrated with a small team.

- Created a Terrain Reasoner that autonomously determines tactical positions and routes using best available information on the current battlespace situation, including terrain, features, cohabitants, and control measures, to aid the robot commander in field decisions.

- Developed planning software that initiates auction services that provide dynamic task allocation services based on risks and rewards for heterogeneous robot teams assigned multiple deliberate or reactive tasks.

- Created the Systems Integration Lab (SIL), a simulation tool employing the planning infrastructure for Autonomous Navigation developed under the Robotics CTA that is being utilized to develop the basis for tactical behaviors and for investigations into the control of unmanned systems by Soldiers.

- Identified a human performance model and the workload elements for predicting performance that will drive Soldier-robot interface development.

PARTNERS

General Dynamics Robotic Systems (GDRS), Lead Industrial Organization, Maryland

Alion Science & Technology (Alion/MA&D), Colorado

Applied Systems Intelligence (ASI), Georgia

BAE Systems (BAE), New Hampshire

PercepTek (P-Tek), Colorado

Robotic Research, LLC (RR), Maryland

Sarnoff Corporation (Sarnoff), New Jersey

Signal Systems Corporation (SSC), Maryland

SRI International (SRI), California

NASA's Jet Propulsion Laboratory (JPL), California

Carnegie Mellon University (CMU), Pennsylvania

Florida A&M University (FAMU), Florida

Howard University (HU), Washington, D.C.

North Carolina A&T State University (NCAT), North Carolina

University of Maryland (UMD), Maryland

RCTA research mitigates the risk of using robots in cluttered and dynamic urban operations environments.

ROBOTICS CTA

PERCEPTION FOR DYNAMIC ENVIRONMENTS

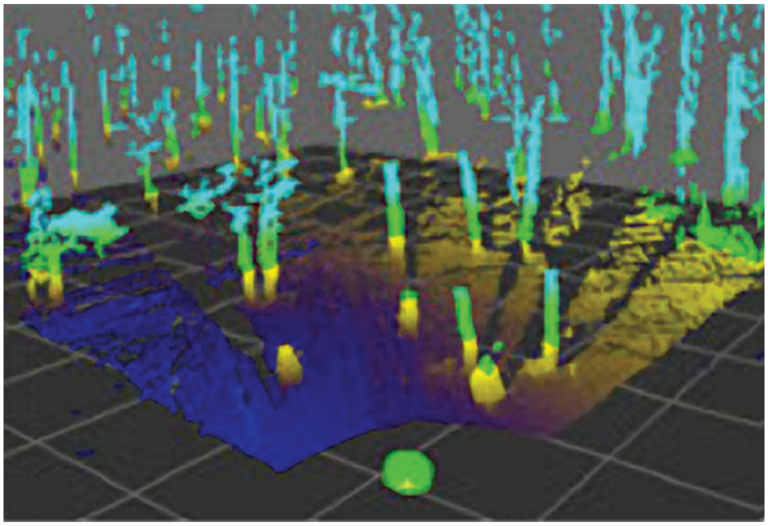
DESCRIPTION

A major challenge in the development of unmanned ground vehicles is the ability to operate safely in the vicinity of humans and other vehicles. This challenge includes the detection of humans in motion at distances long enough to enable high-speed vehicle motion, the detection of humans at rest, the tracking of moving humans over time and the accurate prediction of their future behavior.

We are also investigating algorithms for detecting humans in unusual postures such as crouching, crawling, etc. Correct detection of such situations is critical because non-upright humans are more likely to be confused with "traversable" parts of the terrain. The difficulty is compounded by the fact that non-upright humans are likely to be encountered in off-road situations.

Solving these problems pushes the envelope of what can be achieved with current perception technology. The RCTA has moved aggressively to address these problems, devoting significant research resources to investigate the most successful approaches that can quickly be matured for transition to acquisition programs.

Instead of relying on a single sensor modality and on a single algorithmic approach, the RCTA employs a broad



RCTA research has demonstrated that LADAR scanning can be used to detect moving humans.

range of sensor systems and algorithms to provide as complete an understanding of the battlespace as possible. Specifically, we are developing techniques based on LADARs, video cameras, stereo, infrared and thermal, and radar. We are conducting experimental validation and evaluation of all the techniques on a common instrumented testbed. This approach enables the RCTA to assess the performance of the different methods under different mission conditions, and to design the best combination of techniques, based on this evaluation.

Given the multiple techniques for detection and tracking, we are developing algorithms for fusing their outputs. The fusion mechanism uses a statistical model of each technique, derived from the experimental evaluation, to optimize the combination of algorithms used, given the available sensors.

ACCOMPLISHMENTS

- Developed, integrated and tested advanced computer vision algorithms for people-detection and tracking from a pair of cameras mounted on a moving vehicle, with the goal of detecting people from a moving vehicle.

- Developed, integrated and tested LADAR and video-based moving human and vehicle tracking algorithms on the eXperimental Unmanned Vehicle (XUV).

Robotics technology will be incorporated on manned and unmanned vehicles as part of FCS.


Vision-based human detection.

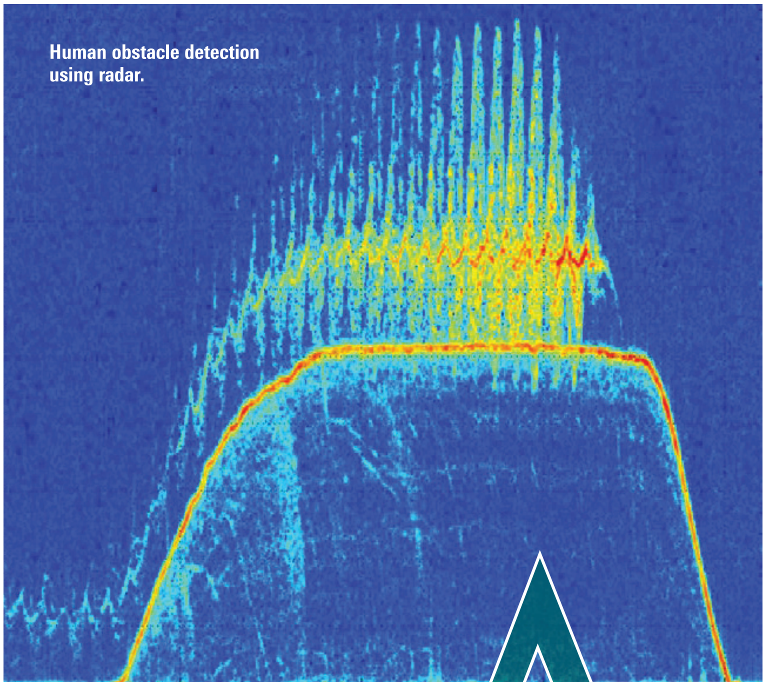
- Used structure and motion cues from a stereo camera pair mounted on a moving vehicle to detect pedestrians who are ahead of the vehicle.

- Investigated the ability to detect and track pedestrians using low cost radar. The data has shown accurate range and angle of arrival (AOA) measurements of a pedestrian beyond 80 meters. We are able to separate the pedestrians from ground clutter while the vehicle is moving.

- Developed a common interface and a common test suite for evaluating and comparing the performance of the detection and tracking approaches. They will be instrumental in selecting a combination of techniques adapted to specific missions and environments, and for gathering the performance statistics necessary for the design of a data fusion mechanism.

PROJECT LEADERS

Dr. Motilal Agrawal, SRI
Dr. Wael Abd-Almageed, UMD
Dr. Mohamed Chouikha, HU
Dr. Larry Davis, UMD
Mr. Greg Kreafle, GDRS
Dr. Kurt Konolige, SRI
Dr. Larry Matthies, JPL
Dr. Daniel Morris, GDRS
Mr. Eric Rundquist, BAE
Dr. Susan Thornton, GDRS


Human obstacle detection using radar.

ROBOTICS CTA

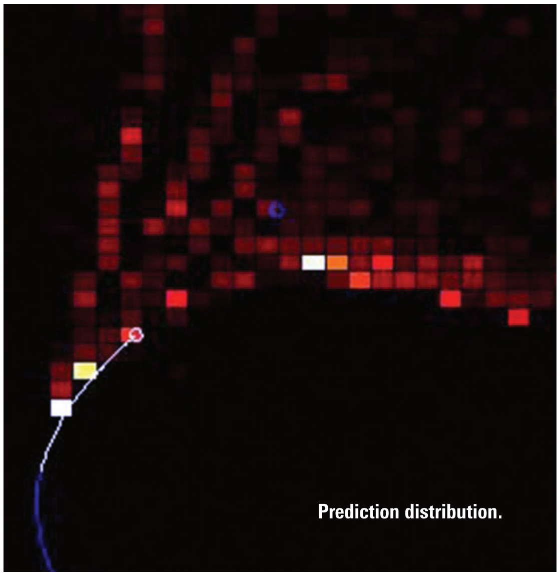
LOCAL SITUATIONAL AWARENESS

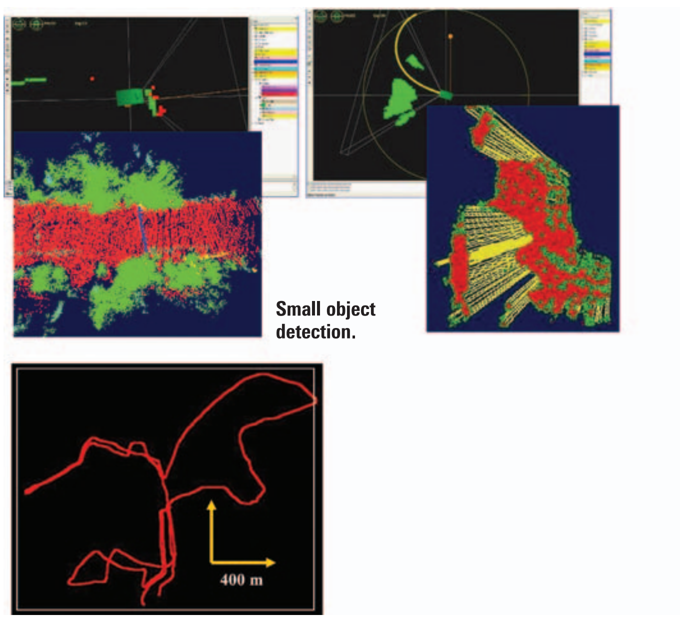
DESCRIPTION

Local situational awareness research focuses on ways to increase the Unmanned Ground Vehicle's (UGV) ability to gather an operational picture of its immediate vicinity so that it can take appropriate action in the presence of humans and moving vehicles.

Our research investigates: predictive obstacle detection to enable maneuver in cluttered environments; algorithms that fuse multiple sensor information to increase the likelihood that UGVs will detect humans and obstacles in time to take the correct action, and the development of a monitoring system that detects moving and stationary people near the UGV.

Our research addresses explicitly the fusion of the dynamic aspects of the UGV's environment (moving people and vehicles) and the static aspects (e.g., the location and type of surfaces and objects in the environment), and reasons about the relations between them, for instance, predicting when an object might appear out of sight of the sensors because of occlusions from another static object.


Prediction distribution.



Small object detection.

Ladar-based obstacle detection and modeling.

Rigorous quantitative testing measures the validity of concepts and solutions to improve local situational awareness. We conducted extensive experimentation by using an instrumented testbed for quantitative evaluation.

By integrating sensors and algorithms on the eXperimental Unmanned Vehicle (XUV), running field tests, and analyzing the acquired data, we are able to determine within the course of a year what directions will prove most promising.

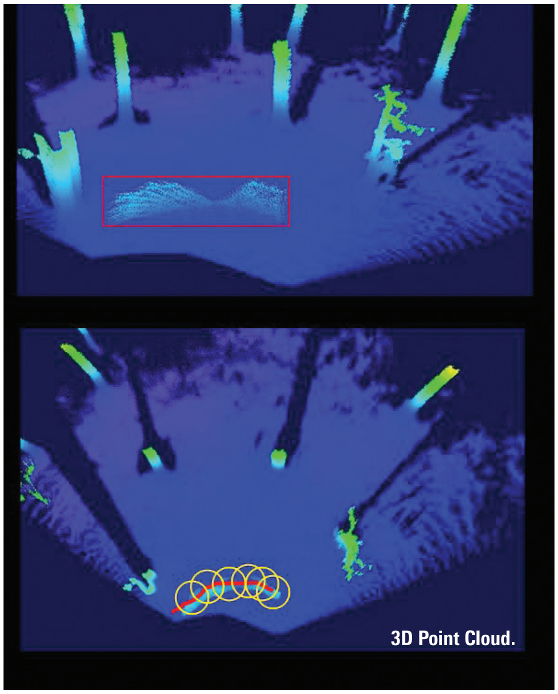
Speed, robustness to occlusions, and the ability to be integrated onto a vehicle are all elements in determining success of a particular approach.

ACCOMPLISHMENTS

- Demonstrated the feasibility of detecting and tracking moving humans and vehicles using LADAR data.

- Integrated detection and tracking algorithms with several LADAR sensors, including single-line Commercial Off-the-Shelf (COTS) sensors for 360-degree coverage, and the GDRS 3D mobility LADAR.

- Integrated detection and tracking algorithms on the XUV and evaluated performance for detecting humans and vehicles.



PROJECT LEADERS

Dr. Martial Hebert, CMU, Perception Task Area Lead

Dr. Paul Haley, GDRS

Dr. Garbis Salgian, Sarnoff

- Showed the feasibility of using 3D Moving Target Indicator (MTI) techniques for tracking humans and vehicles from video cameras. These techniques enable situation awareness around the vehicle and can be used potentially in cluttered environments, such as heavy traffic areas.

- Developed a comprehensive approach to detecting and predicting a moving objects' future behavior based on Hidden Markov Models. Given the trajectory of a tracked object, the current algorithm predicts a distribution of likely trajectories in the future. For example, it enables the prediction of the likely position and velocity of the tracked objects in the future. This capability is critical for the output of the perception algorithms to be used by a mobility planner.

- Interfaced the prediction algorithms with the dynamic planning algorithms. This is a critical step toward autonomous operation in dynamic environments.

ROBOTICS CTA

TERRAIN CHARACTERIZATION

DESCRIPTION

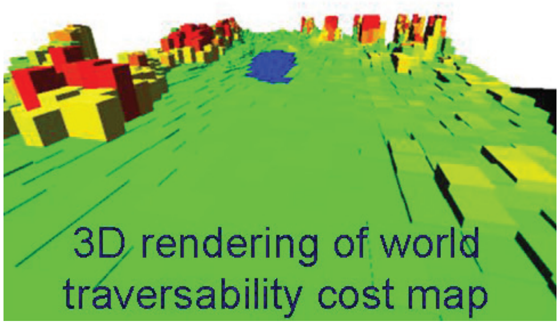
Understanding the terrain within the driving envelope of a vehicle is a critical capability for autonomous mobility. This problem has many facets, from range sensors that can operate at night and in poor weather, to obstacle detection algorithms for obstacles with challenging geometry, to terrain classification, to fusion of multiple algorithms and multiple sensors.

The emphasis of current RCTA terrain characterization research focuses on the extraction of high-level descriptions of the environment from sensor data, and on their use in reasoning about the environment, to enable high-speed driving in challenging environments.

Research objectives include: the development of algorithms for processing sensor data to extract a representation of surfaces and objects that can be used for mobility planning, and to detect and track humans and vehicles; development of a robust water and mud detector for all terrain conditions, including day and night operations; feature detection for operation on structured roadways, and terrain classification in urban environments using multi-sensor (ladar and video) data.

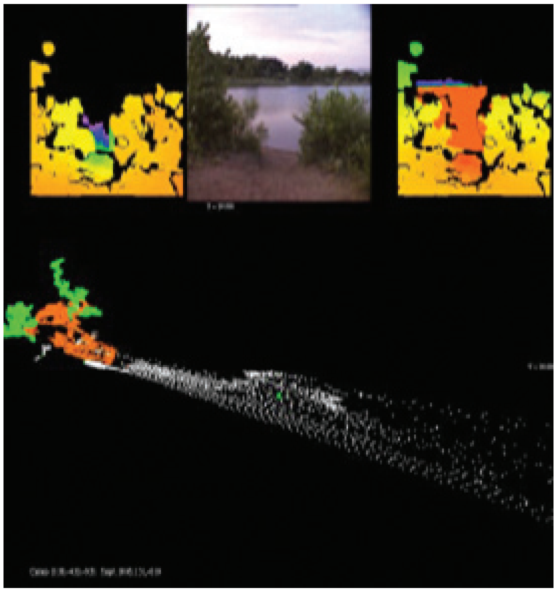
In addition, integration of unmanned systems with humans and manned vehicles in small teams requires that the unmanned system be able not only to sense the presence of others, but to predict their trajectory even in a cluttered environment.

These efforts focus on the development of algorithms that provide speed, are robust to occlusions, and can be integrated into an unmanned vehicle for testing.



The RCTA has demonstrated localizing water in instantaneous and world traversability cost maps.

The Demo III XUV is used to test RCTA-developed terrain characterization solutions.



RCTA perception research includes algorithms for real-time processing of sensor data for detection of water.

PROJECT LEADERS

Dr. Martial Hebert, CMU, Perception Task Area Lead

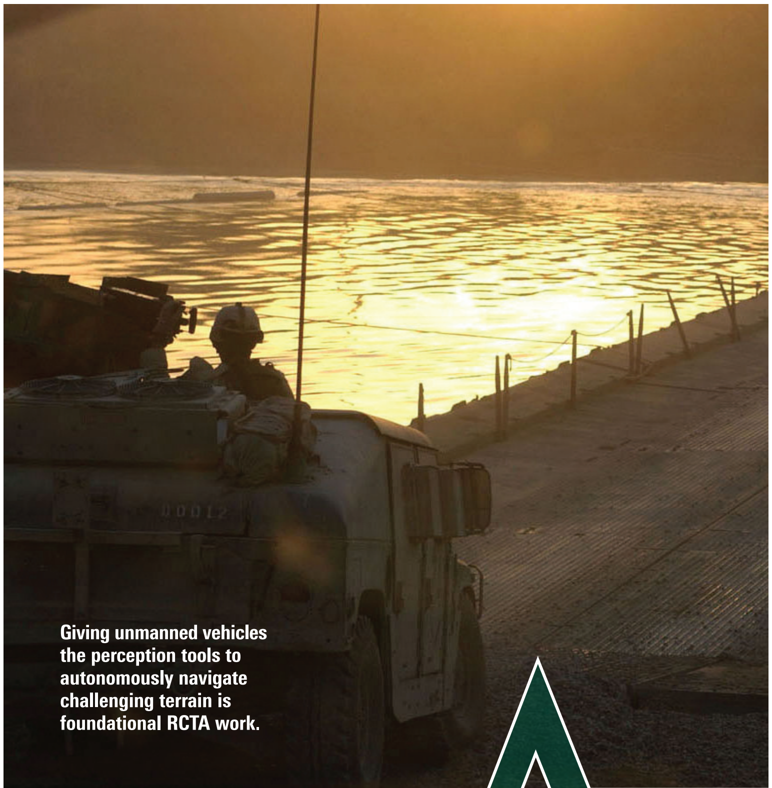
Dr. Patricia Feineigle, GDRS

Dr. William Klarquist, P-Tek

Dr. Larry Matthies, JPL

ACCOMPLISHMENTS

- Development of efficient classifiers with 10-fold increase in performance, and demonstration of the classifiers on the XUV.
- Development of theory and algorithms for automatic selection of optimal scale for 3-D point cloud analysis, and demonstration on XUV LADAR data.
- Development of algorithms for reasoning about visibility and missing data and initial demonstration in the context of detecting negative obstacles.
- Real-time detection of specific terrain types, such as water bodies by combining color, IR, LADAR, and stereo.
- Refinement and extension of a road following system to support high speed vehicle navigation on structured roadways. This capability enables higher-speed operations along known roadways.
- Integration of terrain classification components with section/tracking algorithms for reasoning in dynamic environments.



Giving unmanned vehicles the perception tools to autonomously navigate challenging terrain is foundational RCTA work.

ROBOTICS CTA

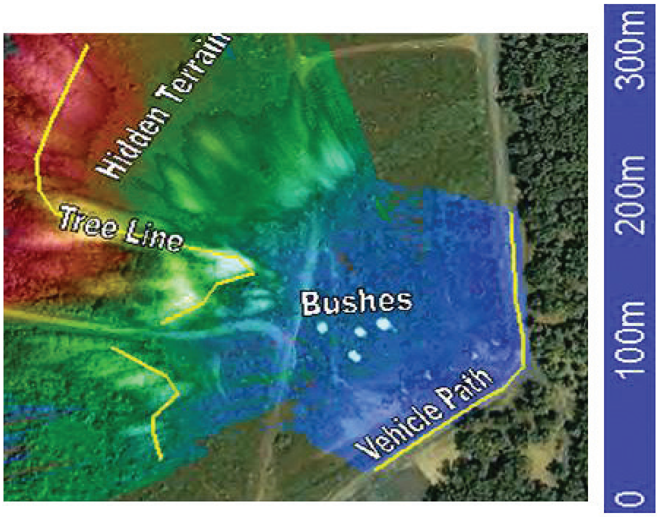
MID-RANGE PERCEPTION

DESCRIPTION

The immediate needs of autonomous mobility rely on sensing at relatively short distances, e.g. up to 100m. However, in order to conduct complex missions, an autonomous system must be able to construct an accurate representation of the environment at medium-range, e.g., up to 500m. What is needed are mid-range sensing techniques with complementary capabilities that correspond to different operational scenarios.

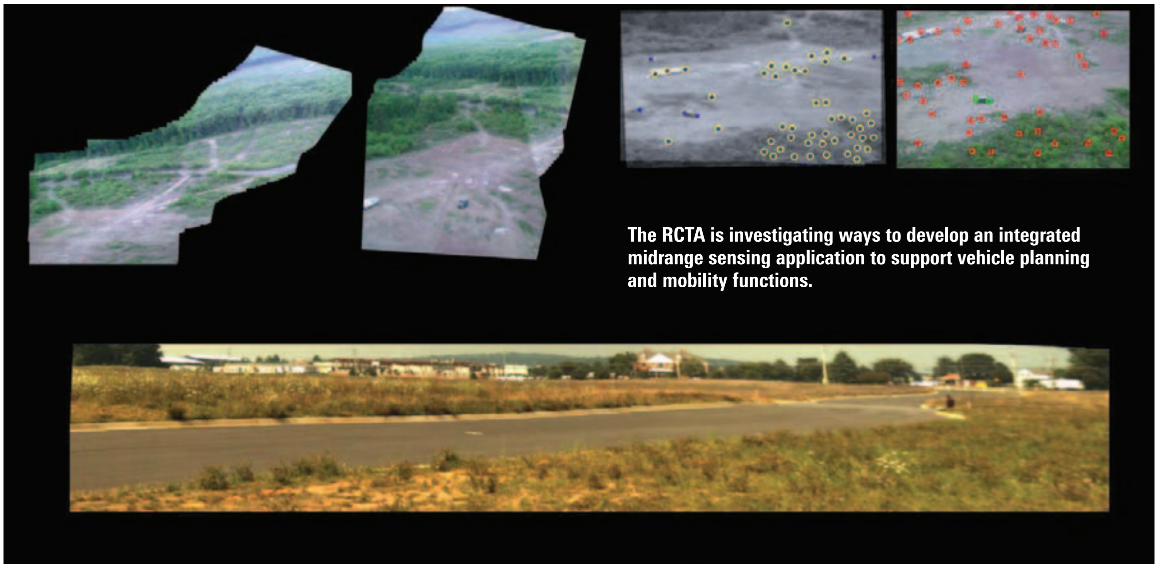
RCTA focus this year is to develop an integrated midrange sensing application to support vehicle planning and mobility functions, and to analyze the performance of the algorithm for applicability to mobility and Reconnaissance Surveillance Targeting and Acquisition (RSTA) planning.

One approach is to convert 3D information into a representation suitable for use in an extended path planning process, in addition to increasing the robustness and accuracy of current structure from motion (SFM) algorithms. Passive techniques, based on motion and stereo, for mid-range structure recovery look promising. But passive depth recovery at mid-ranges, e.g., 500m, requires longer baselines than can be achieved by a practical single stereo system. Longer baselines can be achieved by using cameras on multiple vehicles or by using motion of a single vehicle to establish a long separation between images through temporal integration.

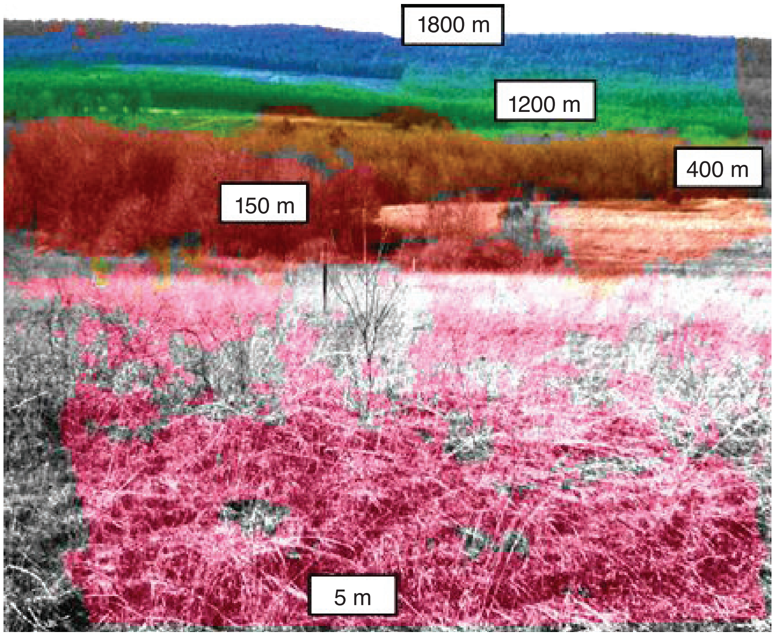


To conduct complex missions, UGVs must be able to 'see' and 'understand' their environment at longer ranges than needed for basic mobility.

An additional modality for mid-range sensing is the use of acoustic sensing for detecting distant noise sources. In FY06, we reduced the volume, mass, and power consumption of the acoustic sensing technology from the XUV and the Vehicle Acoustic Warning and Surveillance (VAWS). In FY07, we continue the development of the small self-contained acoustic sensing unit.



The RCTA is investigating ways to develop an integrated midrange sensing application to support vehicle planning and mobility functions.



Building a longer range view of the world improves UGV situational awareness.

PROJECT LEADERS

Dr. John Fields, Sarnoff

Dr. John Murray, SSC

Dr. Garbis Salgian, Sarnoff

Dr. Minbo Shim, GDRS

ACCOMPLISHMENTS

- Image registration and feature tracking techniques were developed that allow mosaic generation, moving target detection and tracking, and image stabilization on an unmanned platform.
- Registration improvements, including global re-alignment, adaptive mask operations, and sub-mosaic (local image stabilizer) based mosaic construction with respect to a reference sub-mosaic segment of interest, minimizing error propagation throughout the transformation.
- Demonstrated batch SFM algorithm with stereo cameras at Ft. Indiantown Gap, Pa.
- Developed a monocular version that runs on general-purpose processors.
- Designed a flow-through version of the SFM algorithm.

In 2007, the RCTA will integrate midrange perception solutions with planning in field tests on the XUV.

ROBOTICS CTA

AIR/GROUND COLLABORATIVE PERCEPTION

DESCRIPTION

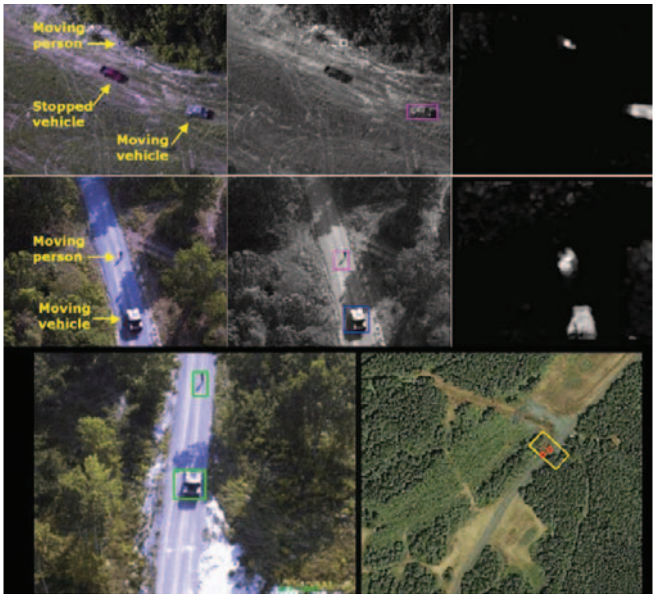
For unmanned air and ground vehicles (UAV/UGV) to effectively carry out missions that support the force, collaborative air/ground technologies must be developed that enable data sharing for detection and tracking.

UAVs provide scene information from a vantage point quite different to that of ground vehicles. This often greatly facilitates detection of obstacles such as ditches, and hill-crests that may be partially occluded when viewed from the ground.

We have developed the capabilities of an autonomous helicopter to include self-sufficient flight, data acquisition from LADAR and video, obstacle detection and avoidance for flight in cluttered environments, communication with a UGV and with the Soldier Machine Interface (SMI), UAV/UGV communication through visual beacon, video registration and mosaicing, and tracking of moving objects from aerial video.

RCTA researchers have developed and demonstrated collaborative operations between unmanned ground vehicles and unmanned aerial vehicles.

Going forward, the first objective is to demonstrate completely GPS-less flight using vision/Inertial Navigation System (INS)/Doppler radar pose estimation. The second objective is to conduct extensive evaluation and demonstration of obstacle detection and avoidance maneuvers. The third objective is to carry out maneuvers to track moving objects based on the Moving Target Indicator (MTI) capabilities already developed under the RCTA.



RCTA research includes a focus on developing ways that unmanned air vehicles can assess, analyze, and transmit information about ground conditions to unmanned ground vehicles.

PROJECT LEADERS

Dr. Omead Amidi, CMU

Dr. Garbis Salgian, Sarnoff

ACCOMPLISHMENTS

- Detection and tracking of humans from aerial video in support of ground vehicles' operations.
- Tested the MTI algorithm on multiple sequences from the set collected in field tests and verified that the algorithm can handle the typical scenarios: people and vehicles moving in open areas, next to tree lines or along roads in wooded areas.
- Obstacle detection and avoidance using a forward looking, single plane LADAR and 3D planning algorithms for autonomous flight in cluttered environments.
- Autonomous flight with reduced GPS and in cluttered environments, which will enable Soldiers to direct unmanned air and ground assets for reconnaissance missions.
- Developed a new stabilization system for real-time stabilization of the imagery from a UAV-mounted wide angle camera, which is used in support of MTI and navigation.

The RCTA uses an RMAX unmanned air vehicle in its investigation of collaborative unmanned air and ground vehicle operations.

ROBOTICS CTA

PATH PLANNING FOR DYNAMIC ENVIRONMENTS

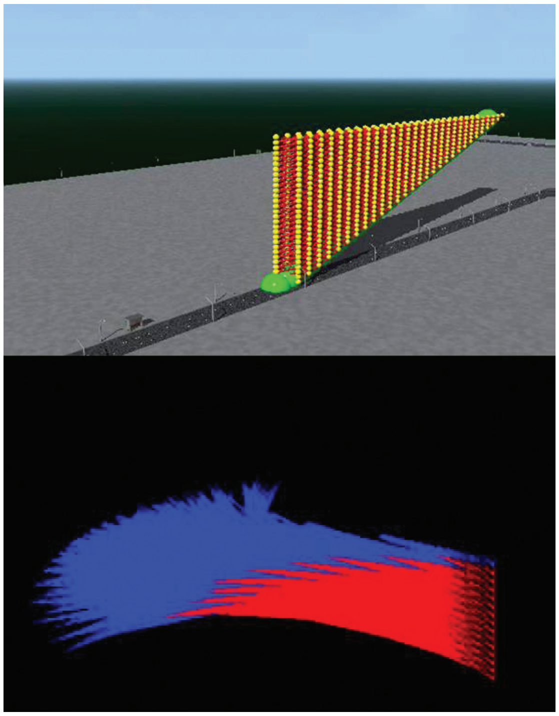
DESCRIPTION

One of the mission-critical capabilities necessary for unmanned ground vehicles to integrate effectively with ground troops will be high speed navigation in crowded environments alongside moving vehicles and people.

We are striving to push the UGV performance envelope by negotiating more difficult terrains at higher speeds. The performance of autonomous navigation can be improved if the vehicle's control system takes into account the type of terrain on which the vehicle is traveling, for example, loose gravel, loose sand, mud, etc., which may be difficult to determine by relying exclusively on perceptions sensors.

To address this problem, we have developed a neural network algorithm capable of identifying terrains based on surface-induced robot acceleration and vehicle wheel slip. This algorithm is very accurate in predicting terrain type.

In addition to increasing speed, we are pushing effective navigation into more cluttered and dynamic environments, such as densely wooded areas and urban terrain. To complement our feed forward and adaptive approaches



Moving obstacles as a probability density function.

For robots to go anywhere at any time, the vehicle's control system must take into account the type of terrain on which the vehicle is traveling.

to the problem, we are investigating fuzzy logic-based algorithms that mimic human performance. In FY06 the need to develop planning approaches that incorporate dynamic models led to substantial breakthroughs.

We are also working on a field interface planner that will increase the mobility of a vehicle by allowing cost information exchange between the Autonomous Mobility (AM) (low level) and the Autonomous Command and Control (ACC) (high level) planning levels. "Field" refers to a continuous ring of cost-to-goal data passed from the higher level to the lower, as opposed to a single waypoint toward which the low level planner would navigate.

In addition, we created a new approach that adds time as another planning dimension, allowing the planner to not only take optimal paths, but to do it at optimal speed. The old system would wait for the moving obstacle to move out of the path or it would re-plan each cycle to avoid dynamic objects. By adding time to our solution, the vehicle can change speed throughout the trajectory and generate a smoother solution to obstacle avoidance.

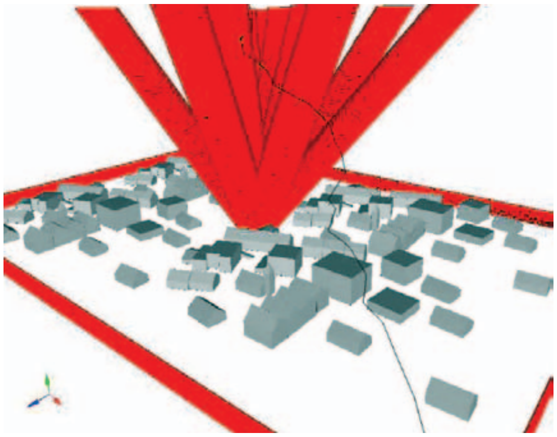
PROJECT LEADERS

Dr. Emmanuel Collins, FAMU

Mr. Damion Dunlap, FAMU

Dr. Alberto Lacaze, Robotic Research, LLC

Dr. Anthony Stentz, CMU, ICA Task Area Lead



Dynamic planning with moving vehicles.

ACCOMPLISHMENTS

- Developed the Discretized Model Predictive Control (DMPC), which accomplishes path planning in the presence of constraints using dynamic models. DMPC deals with constraints that include obstacles, stability constraints, limitations on actuator amplitude, maximum vibration amplitude, and so on.

- DMPC will enable development of path planning solutions for climbing steep hills, operating at high speeds in the presence of stationary and dynamic obstacles or in cases of mechanical failure without expanding the planning space.

- Employed a fully developed Neutral Messaging Language (NML) channel that communicates between the dynamic planning algorithm and the object detection and classification algorithm.

- Set the stage for implementing two-way communication to incorporate passing information about detected obstacles from the low level to the high level planner that will enable the robot to “decide” more quickly how to proceed in dynamic and cluttered environments.

- Introduced a real-world simulator based on a video game to provide a realistic and safe testbed for path planning applications to enable virtual path planner testing.

RCTA research has developed a neural network algorithm capable of identifying terrains based on surface-induced robot acceleration and vehicle wheel slip.

ROBOTICS CTA

MISSION PLANNING

DESCRIPTION

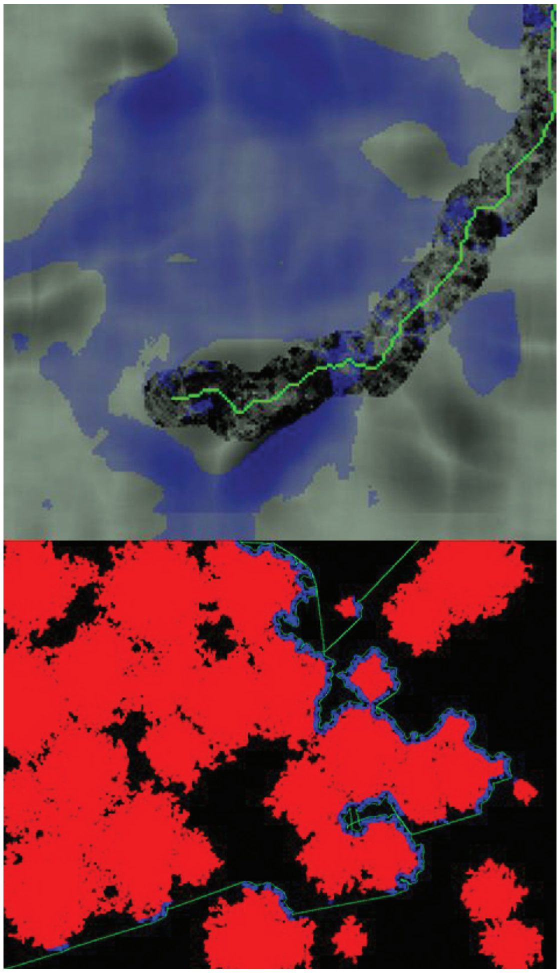
Route planning is a critical technology for autonomous vehicles, both ground and air.

We have developed an extensive planning capability that reasons about geometric information, including routes, mobility, inter-visibility, sensor coverage, communications, stealth, risk, formations, perimeter maintenance, guarding, etc., and re-plans in real time in response to changing conditions, tasks, and new information.

Our planners can minimize weighted multi-metric cost functions, satisfy multiple hard constraints, model uncertainty in both vehicle pose and map data, and handle expansive environments.

We rolled up much of this capability into the Geometric Path Planner (GPP), which has been used by the Operator Control Unit to plan routes for XUVs and Pointer vehicles.

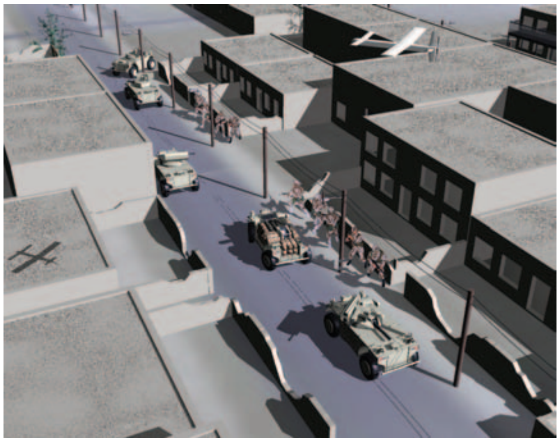
We have extended our algorithms to plan for multiple vehicles, thus improving the performance of our market-based vehicle coordination scheme, and to account for moving adversaries in the tactical environment.



To ensure that unmanned vehicles will be effective co-combatants, the RCTA is developing and testing autonomous planning capabilities.

ACCOMPLISHMENTS

- Geometric path planner provides real-time planning / re-planning algorithms to move ground and air vehicles from one location to another, optimizing mission metrics such as mobility, time, intervisibility and sensor coverage while satisfying constraints and using multi-resolution terrain databases.
- Terrain Reasoner autonomously determines tactical positions and routes using best available information on the current battlespace situation to include terrain, features, cohabitants, and control measures.



RCTA-developed planning technology will enable multiple robots to act cooperatively on missions.

- Symbolic Reasoner understands electronic mission orders, task organization, and risk vs. reward value judgment to provide mission-situated, task-level autonomous command and control of unmanned systems allowing them to conduct stealthy cooperative movement, reconnaissance and observation operations, and react to enemy contact.

- The Probabilistic Planning with Clear Preferences (PPCP) algorithm enables planning a route for a vehicle in the presence of possible adversaries so that the robot will be able to execute tactical behaviors.

- Combined our path planner with vehicle uncertainty with a ladar-based registration system and demonstrated the ability to plan and execute routes without GPS so that robots can continue to operate in GPS-denied environments.

- Developed a Rapidly-exploring Random Tree (RRT) planner for solving the constrained exploration problem and extended the algorithm to re-plan rapidly and to improve its solution over time.

- Merged our planning with vehicle pose uncertainty with perception to plan routes that register sensor data to an overhead map to reduce vehicle uncertainty.

- Extended our algorithms to plan for multiple vehicles, thus improving the performance of our market-based vehicle coordination scheme, and to account for moving adversaries in the tactical environment.

PROJECT LEADER

Dr. Anthony Stentz, CMU, ICA Task Area Lead

RCTA planning research is developing tools that will enable unmanned systems to operate autonomously regardless of terrain, GPS, or task complexity.

ROBOTICS CTA

MULTI-ROBOT COLLABORATION

DESCRIPTION

For unmanned systems to be successful co-combatants in small combat units with Soldiers, it is critical that they be able to work collaboratively, not only with their human commanders but with other unmanned systems.

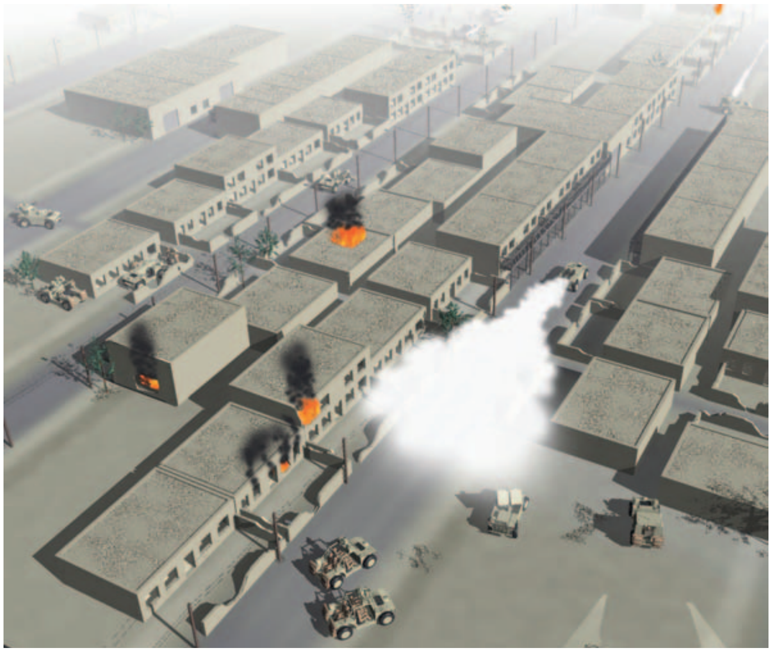
We have envisioned a scenario in which robots would be tasked as a team to carry out various missions in order to develop a realistic task set and decompose those tasks to develop a systematic approach to collaboration.

We have developed a market-based approach for a team of unmanned assets to mutually determine their individual roles and task assignments and to coordinate their actions in response to a mission order.

Under such an approach, a team of vehicles negotiate amongst each other to maximize revenue (by accomplishing the mission) and minimize cost (by consuming as few resources as possible).

This process is accomplished without relying on any single vehicle to make assignments; instead, the assignments are mutually agreed upon via peer-to-peer interactions. The approach includes a task description format, negotiation protocol, and optimization tool for mapping tasks onto assets.

For robots to be useful to small combat teams in the field, they must be able to engage in collaborative missions.



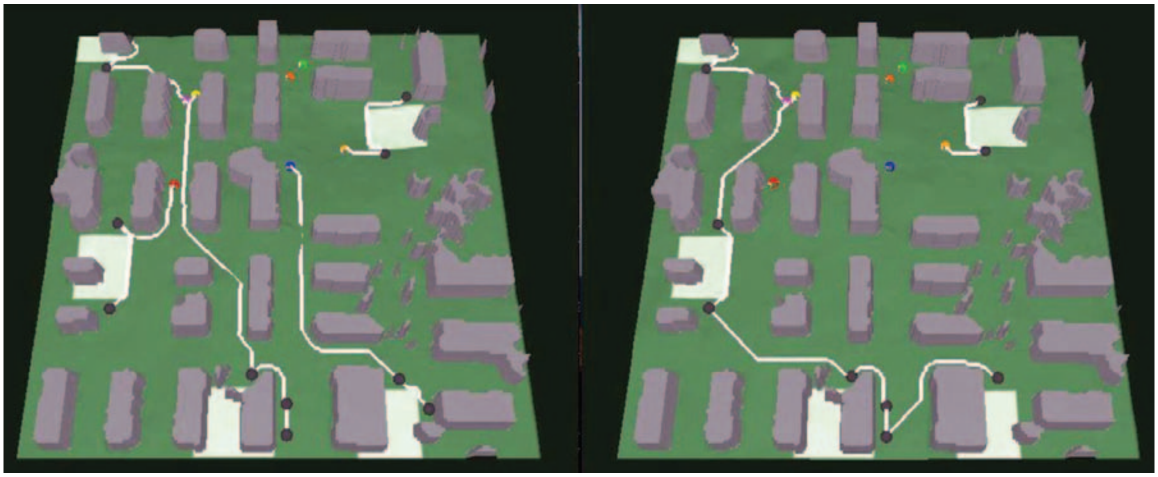
For robots to be force multipliers on the battlefield, they must be able to operate collaboratively.

It has been applied to distributed mapping, area reconnaissance, perimeter sweeping, and constrained exploration.

Successfully deployed, this control algorithm will enable Soldiers to send out teams of robots on a mission and know that it will be accomplished in a time and cost effective way.

ACCOMPLISHMENTS

- Extended the market-based architecture to handle time-based emergency response functions.
- Developed a task tree mechanism that allows complex tasks to be represented at an abstract level and exchanged quickly.
- Developed mechanisms to permit task trees to be selectively decomposed, improving runtime without impacting the quality of the solution.



Task trees with time metric.

- Imported roadmap planning techniques to permit the robots to plan over longer horizons and produce more optimal solutions.

PROJECT LEADER

Dr. Anthony Stentz, CMU, ICA Task Area Lead

ROBOTICS CTA

INTELLIGENT CONTROL FOR SAFE AND SECURE MOVEMENT

DESCRIPTION

When an unmanned system competently applies its move, look, shoot and communicate skills to perform a role as a member of a small team in a realistic environment, we say it is behaving tactically.

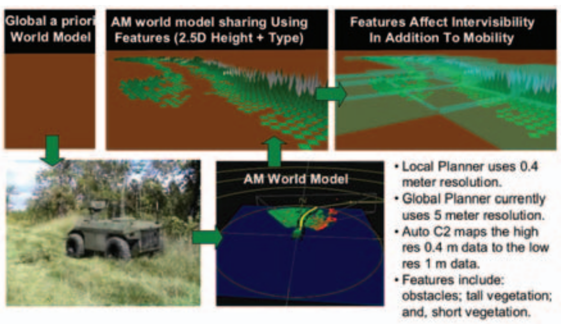
The goal of this project is to develop the capability to coordinate perception based skills and to interact with humans and information systems in a manner that enables the unmanned system to act in a safe and secure manner in support of mission objectives.

We have defined and refined a systematic process for identifying and specifying tactical behaviors; this process is simple to apply and is technology independent but works hand in hand with our intelligent control approach.

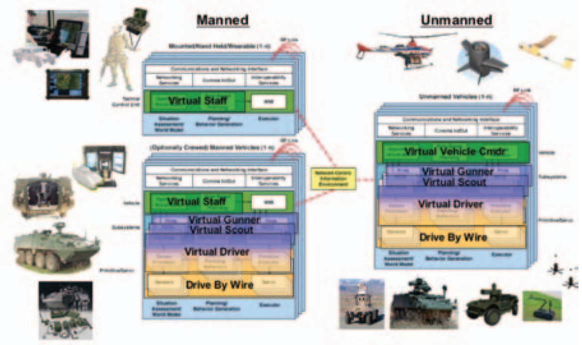
Our behavior identification focused on moving securely as a small team from Point A to Point B.

Secure movement behaviors include several key processes (individual level troop leading procedures, risk management, mutual support, five-point contingency planning, and actions on contact) and multiple, interrelated behaviors (terrain oriented recon, determining tactical positions and routes, maintaining local security, employing terrain for cover and concealment, and battle drills).

We have fleshed out the 4-Dimensional Real Time Control System (4D/RCS) architectural framework capable of fusing perception, world modeling, planning, and control



Global and Local Planner integration for robust mobility in unknown environments.



System of Systems (SoS) intelligent control deployment model.

technologies in a system of systems manner to seamlessly integrate distributed autonomous components.

The framework integrates key components, including the Warfighter's Machine Interface (WMI), Autonomous Command and Control (ACC), Autonomous Mobility System (AMS), and autonomous Reconnaissance Surveillance Target and Acquisition (RSTA).

These components, when integrated using our intelligent control approach, implement the skills that result in the unmanned system behaving tactically.

The primary technology being developed is an ACC application service that can act as either a decision support system when directly aiding a Soldier, or as a virtual vehicle commander (VC) of an unmanned system.

As a VC, the ACC makes the unmanned system mission aware and able to assume a role on a team; allows it to accept, understand and decompose task level directives; coordinates perception based move and look skills; and, communicates with the team and with enterprise information systems.

The ACC works with the WMI, AMS and RSTA to interact with the Soldier, interact with information systems and to competently perform complex tactical behaviors.

ACCOMPLISHMENTS

- Developed service-based, open architecture core reasoning engine that readily integrates with any information source (e.g. human, information systems, perception system) and allows autonomous C2 technologies (e.g. operational command language parser, auction services, terrain reasoning services, inference engine, plan decomposition rules, execution monitoring rules, Soldier alerting rules, etc.) to operate on that information as it becomes available.

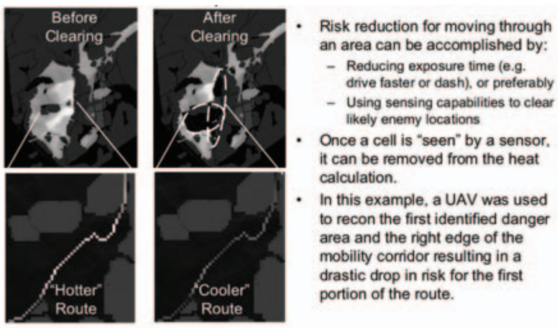
- Developed operational command language to support task level human-robotic interactions.

- Developed capability that autonomously determines tactical positions and routes using best available information on the current battlespace situation to include terrain, features, cohabitants, and control measures shared by either local sensors, off-board sensors, or the Soldier.

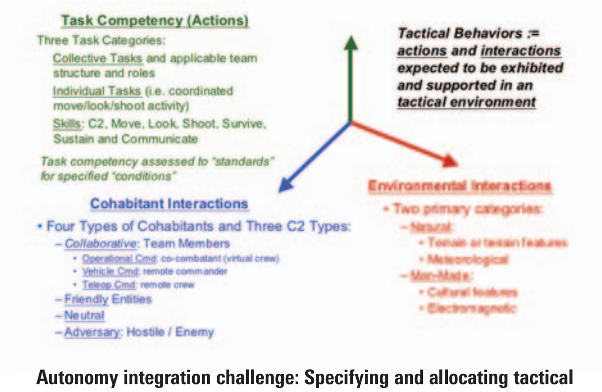
- Added threat cost layer to terrain reasoner that uses knowledge of terrain to predict "where to look" for secure movement.

- Developed risk versus reward value system used to direct task allocations performed by the auction services and to tailor plan decomposition and specialization to reflect the current situation.

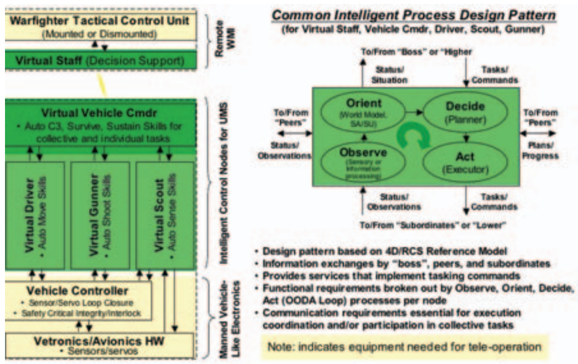
- Field-demonstrated, system of systems intelligent control functional architecture allowing UGVs, UAVs and UGS to be seamlessly integrated with a small team.



"Where to Look" based on the Soldier's continuous, informal process.



Autonomy integration challenge: Specifying and allocating tactical behaviors.



What makes it "Intelligent"?

PROJECT LEADERS

Mr. Dan Rodgers, GDRS, ICA Integration Lead

Mr. Bill Dodson, GDRS

Mr. Lyle Sutton, GDRS

Mr. Robert Dean, GDRS

Mr. Louis Barbieri, GDRS

HUMAN-ROBOT INTERACTION

DESCRIPTION

The goal of the RCTA Human-Robot interaction approach is to ensure that the Soldier will be able to operate, maintain, and support future robotic systems in the battlefield at operational tempo. Placing the Soldier at the center of our robotic system development efforts dramatically influences the design and development of effective Human-Robot technologies that are part of an overall human performance modeling process.

Tomorrow's Soldier will be asked to perform complex cognitive tasks that require timely and competent decision making in conjunction with robotic systems that have varying levels of autonomy and are designed for a range of missions. RCTA researchers are developing the foundational concepts and technologies for facilitating that interaction.

Our research pays special attention to human factors issues, including, but not limited to robotic span of control, determination of the number of autonomous robotic assets able to be commanded by a single operator, and the command and control issues of the Soldier/robotic system in relation to other manned and unmanned assets for small combat team operations.

In association with our human factors research, we have developed a family of mounted and dismounted Tactical Control Unit (TCU) testbeds for control of robotic assets, including both ground and air vehicles. These testbeds provide a research interface for control of robotic systems, as well as reporting and situational awareness through an integrated mapping and asset control system that allows research focused on understanding how to maximize the transfer of information and understanding between robot and Soldier.

RCTA researchers have developed scalable interfaces for mounted and dismounted operations.

The Soldier-Robot interface developed by the RCTA enables researchers to investigate how Soldiers deal with complex cognitive tasks.

We have also been focused on developing a Spoken Language Interface (SLI) for command and control applications using SRI's DynaSpeak automatic speech recognition technology. In particular, investigating how an SLI can be effective for controlling multiple robotic platforms and sensors in a noisy vehicular environment. We have also developed a Systems Integration Laboratory (SIL), a simulation tool employing our planning infrastructure that is being utilized to develop the basis for tactical behaviors. It is being utilized by ARL/HRED and its partners in the ADA CTA for investigations into the control of unmanned systems by Soldiers.

multiple robotic platforms and sensors in a noisy vehicular environment.

• Integrated Cross-Consortia DARE interface technologies from the ADA CTA that allows agent based integration to all ADA technologies.

PROJECT LEADERS

Mr. Dave Dahn, Alion, HMI Task Area Lead

Mr. Brian Koetting, GDRS, HMI Integration Lead

Dr. Cregg Cowan, SRI

Dr. Mike Frandsen, SRI

Dr. Marc Gacy, Alion

Dr. Greg Myers, SRI

Ms. Stacey Quesada, Alion

ACCOMPLISHMENTS

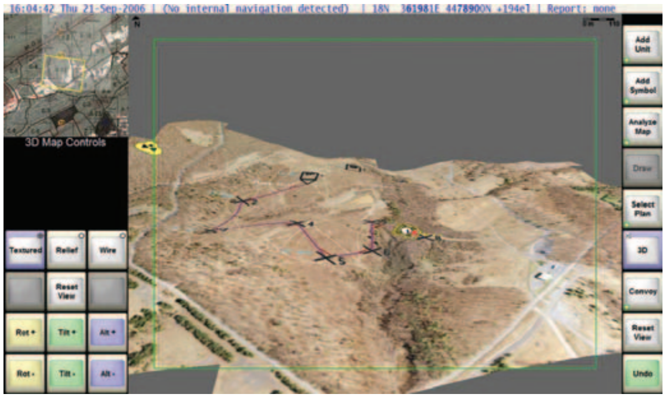
• Developed a multi-modal Tactical Control Unit (TCU) with a scalable Soldier-Machine Interface (SMI) that enables us to test how Soldiers will command and control multiple, different unmanned systems at the same time.

• Developed a family of TCUs for mounted and dismounted use with a different emphasis in each TCU category (mounted, dismounted leaders tablet, and individual Soldier system) based on the information and functional priorities Soldiers are expected to have in anticipated operational and environmental conditions.

• Connected the TCU interface to a virtual environment for training and mission planning, as well as Soldier experimentation and feedback.

• Redesigned control architecture and interface to ensure the system would decrease Soldier workload and improve C2.

• Developed a Spoken Language Interface (SLI) for command and control applications for controlling



The RCTA Soldier-Robot interface enables the operator to get a three dimensional view of the terrain the unmanned vehicles are traversing.

APPENDIX: LIST OF ACRONYMS

1CD 1st Combat Division
3-D Three Dimensional
4D/RCS 4-Dimension Real-time Control System
4H-SiC Hexagonal unit cell Silicon carbide
ACC Autonomous Command and Control
ACT-R Adaptive Control of Thought-Rational
ADA CTA Advanced Decision Architectures Collaborative Technology Alliance
AFRL Air Force Research Laboratory
AI Artificial Intelligence
AJCN Adaptive Joint CISR Node
Al Aluminum
AM Autonomous Mobility
AMPGEN Advanced Micro Power Generators
AMS Autonomous Mobility System
ANS Autonomous Navigation System
AO Acousto-Optic
AOA Angle of Arrival
AOTF Acousto-Optic Tunable Filter
AODV Ad-Hoc On-Demand Distance Vector (Routing)
APU Auxiliary Power Unit
ARDEC Armaments RDE Center
ARI Army Research Institute
ARL Army Research Laboratory
ASCTA Advanced Sensors Collaborative Technology Alliance
ATD Advanced Technology Demonstration
ATO Army Technology Objective
ATR Automatic Target Recognition
ATRV All-Terrain Robotic Vehicle

AVOSCET Autonomous Vehicle Operator Span of Control Evaluation Tool
BCBL Battle Command Battle Lab
BJTs Bipolar Junction Transistors
C2 Command and Control
C3I Command Control Communication Intelligence
C3TRACE Command, Control, and Communication Techniques for Reliable Assessment of Concepts Enhancement
C4ISR Command, Control, Communications, Computers, Intelligence, Surveillance and Reconaissance
CAM Collaborative Alliance Manager
CCIR Commanders Critical Information Requirements
C&N CTA Communications & Networks CTA
CBR Component Based Routing
CDMA Code Division Multiple Access
CERDEC Communications and Electronics Research, Development and Engineering Center
CHPS Combat Hybrid Power Systems
CIA Central Intelligence Agency
CISD Computational and Information Sciences Directorate
CISR Communications, Intelligence, Surveillance and Reconnaissance
CPO Catalytic Partial Oxidation
CMC Consortium Management Committee
CMU Carnegie Mellon University
CMT Concurrent Multipath Transfer
CO Carbon Monoxide
COA Course of Action
COE Corps of Engineers
CONOPS Concept and Operations
COP Common Operating Picture
COTS Commercial Off-The-Shelf
CPOX Catalytic Partial Oxidation
CSEL Cognitive Systems Engineering Laboratory
CSI Channel State Information
CSLANT Collaborative SLide ANnotation Tool
CT Cognitive Task
CTA Collaborative Technology Alliance
CTAC Collaborative Technology Alliance Conference
Cu Copper
CW Continuous Wave
DA Directional Antenna
DARE Decision Architecture Research Environment
DARPA Defense Advanced Research Projects Agency
dB decibel
DC Direct Current
DCD Decision-Centered Design
DDF Decentralized Data Fusion
DDNS Dynamic Domain Name Service
DIF Dataflow Interchange Format
DHS Double Helical Signature
DMFC Direct Methanol Fuel Cell
DMPC Discretized Model Predictive Control

DNS Domain Name System
DoD Department of Defense
DRIE Deep Reactive Ion Etching
DROP Deployed Research Operational Platform
DSRP Dynamic Survivable Server Pooling
DSRC-T Distributed Survivable Resource Control-Tactical
DTE Dynamic Trust Establishment
DTAL Deputy Technical Area Lead
EO Electro Optic
ESA Electronically Scanned Array
ESB Executive Steering Board
ESR Electron Spin Resonance
FCS Future Combat Systems
FDFR Full-Diversity Full-Rate
FDMA Frequency Division Multiple Access
FEA Finite Element Analysis
FFH Fast Frequency Hopping
FFRDC Federally Funded Research and Development Center
FFW Future Force Warrior
FH Frequency Hopping
FLA Filter Lens Array
FM Frequency Modulation
FMCW Frequency Modulation Continuous Wave
FPA Focal Plane Array
fps frames per second
FTP File Transfer Protocol
FY fiscal year
GaAs Gallium Arsenide
GaN Gallium Nitride
GaSb Gallium Antimonide
GBMC2 Ground-Based Missile Defense Command and Control
GDLS General Dynamics Land Systems
GF Galois Field
GHz Gigahertz
GMC Generalized Multi-Carrier
GPP Geometric Path Planner
GPS Global Positioning System
GRBIL GRaph-Based Interface Language
H2S Hydrogen Sulphide
HAIPE High Assurance Internet Protocol Encryptor
HBCU Historically Black College or University
HEMT High Electron Mobility Transistor
HEMTT Heavy Expanded Mobility Tactical Truck
HMI Human Machine Interface
HMMWV High Mobility Multi-purpose Wheeled Vehicle
HPS Hybrid Power System
HRED Human Research & Engineering Directorate
HSI Hyperspectral Imaging
ICA Intelligent Control Architectures
ICI Inter-Carrier Interference
IED Improvised Explosive Device
IEEE Institute of Electrical and Electronics Engineers
IETF Internet Engineering Task Force
IMPRINT Improved Performance Research Integration Tool
InAs Indium Arsenide
INS Inertial Navigation System
ID Infantry Division
INSCOM Intelligence and Security Command
IP Internet Protocol
IPPF Independent Partition Particle Filter
IPSec Internet Protocol Security
IR Infrared
ISR Intelligence Surveillance Reconnaissance
IUGS Internetted, unattended ground sensors
JAUS Joint Architecture for Unmanned Systems
JCATS Joint Combat Tactical Simulation
JFCOM Joint Forces Command Center
JGRE Joint Ground Robotics Enterprise
JP8 Jet Propellant
JTRS Joint Tactical Radio System
Ka band 27-40 GHz Microwave Band
KAoS Knowledgeable Agent Oriented System
KM Key Management
Ladar Laser Detection and Ranging (Laser Radar)
LADAR Laser Radar
LAIR Laboratory for Artificial Intelligence Research
LAMD Lightweight Airborne Minefield Detection
LCF Linear Complex Field
LED Light Emitting Diode
Li Lithium
LIO Lead Industrial Organization

APPENDIX: LIST OF ACRONYMS

LNS Logical Name System
LOS Line-of-sight (communications)
LPD Low Probability of Detection
LPI Low Probability of Interception
LTG Low Temperature Growth
LWIR Long Wave IR
MA&D Micro Analysis and Design
MAC Medium Access Control
MANET Mobile Ad-Hoc Network
MANPRINT Manpower, Personnel and Training Integration
MARCON-i Multi-Dimensional Assured, Robust, Communications for an On-the-Move Network
MBE Molecular Beam Epitaxy
Mbps Mega bits per second
MC Multi-Carrier
MCS Maneuver Control System
MCT Mercury Cadmium Telluride
MEA Membrane Electrode Assembly
MEMS Micro-Electro-Mechanical Systems
MHEMT Metamorphic High Electron Mobility Transistor
MILCOM Military Communications (conference)
MIMO Multiple-Input Multiple-Output
MIP Mobile IP
MIT Massachusetts Institutes of Technology
MIUGS Micro Internetted Unattended Ground Sensor
MMIC Monolithic Microwave Integrated Circuit
MMW Millimeter Wave
MONOPATI Multi-Objective Network Optimization and Assessment Tool
MOS Metal Oxide Semiconductor

MOSFET Metal-Oxide Semiconductor Field-Effect Transistor
MOSAIC Multi-functional On-the-move Secure Adaptive Integrated Communications
MOUT Military Operations in Urban Terrain
M&S Mobility and survivability
m/s Meter per Second
MSM Metal Semiconductor Metal
MTI Moving Target Indicator
mW milliwatts
MWIR Millimeter Wave Infrared
NASA National Aeronautics and Space Administration
Nb Niobium
Nb2O5 Niobium Oxide
NiCad Nickel-Cadmium
NBI Narrowband Interference
NIMA National Imagery and Mapping Agency
NIST National Institute of Standards and Technology
NOMADS Neurally Organized Mobile Adaptive Device
NRL Naval Research Laboratory
NRO National Reconnaissance Office
NML Neutral Modeling Language
NML Network Messaging Language
NSC Natick Soldier Center
NVESD Night Vision and Electronic Sensors Directorate
O Oxygen
OAV Organic Air Vehicle
OCL Operational Command Language
OCU Operator Control Unit
OFDM Orthogonal Frequency Division Multiplexing
OFDMA Orthogonal Frequency-Division Multiple Access
OFW Objective Force Warrior
OGA Other Government Agency
OneSAF One Semi-Automated Forces
ONR Office of Naval Research
O&O Organization and operation
OPORD Operation Order
ORA Organizational Risk Analyzer
OSD Office of the Secretary of Defense
OTBSAF OneSAF Testbed Baseline
PAPR Peak-to-Average Power Ratio
Pd Palladium
PDA Personal Data Assistant
P&E Power and Energy CTA
PEM Proton Exchange Membrane
PEMFC Proton Exchange Membrane Fuel Cells
PHEMT Pseudomorphic High Electron Mobility Transistor
PILSNER Proactive Integrated Link Selection for Network Robustness
PIMRC Personal, Indoor and Mobile Radio Communications (conference)
Pt Platinum
QoS Quality-of-Service
QWIP Quantum Well Infrared Photoconductor

RCTA Robotics Collaborative Technology Alliance
RCS Radar Cross Section
R-CAST RPD enabled - Collaborative Agents Simulating Teamwork
R&D Research and Development
RDECOM Research, Development and Engineering Command
RDEC Research, Development and Engineering Center
RDT&E Research, Development, Test & Evaluation
RF Radio Frequency
RHFC Reformed Hydrogen Fuel Cell
RISTA Reconnaissance Intelligence Surveillance and Target Acquisition
RMB Research Management Board
ROIC Read Out Integrated Circuit
ROP Robotic Obscurant Program
ROTC Reserve Officers' Training Corps
RPD Recognition-Primed Decision Making
RRT Rapidly-exploring Random Tree
RSTA Reconnaissance, Surveillance, Target and Acquisition
RTSPI Real-Time Spectro Polarimetric Imaging
Ru Ruthenium
SA Situation Awareness
SAR Synthetic Aperture Radar
S&T Science & Technology
SCTP Stream Control Transmission Protocol
SC Single-Carrier
SEM Scanning Electron Microscope
SF System Failures
SFM Structure From Motion
SiC Silicon Carbide
SID Session Identifier
SiGe Silicon Germanium
SIL System Integration Laboratory
SIP Session Initiation Protocol
SLAM Simultaneous localization and mapping
SLI Spoken language interface
SLS Stained Layer Superlattice
SMI Soldier Machine Interface
SOFC Solid Oxide Fuel Cell
SS Spread Spectrum
STF Space Time Frequency
STIC Simulation and Training Technology Center
STO Science and Technology Objective
STTR Small Business Technology Transfer
T/R Transmit/Receive
TAL Technical Area Lead
TARDEC Tank Automotive Research, Development and Engineering Center
TCP Transmission Control Protocol
TDMA Time Multiple Access
TEALab Tactical Environment Assurance Laboratory
TOO Targets of Opportunity
TOS Tactical Object and Graphics
TRADOC Training and Doctrine Command
TRL Technology Readiness Level
TWNA Tactical Wireless Network Assurance
UACO Unmanned Autonomous Collaborative Operations
UAVs Unmanned Aerial Vehicles
UE Unit of Employment
UGS Unattended Ground Sensors
UGVs Unmanned Ground Vehicles
UML Universal Modeling Language
UP Unitary Precoded
USMA U.S. Military Academy
USV Unmanned Surface Vehicles
V Volt
VAWS Vehicle Acoustic Warning and Surveillance
VB Virtual Backbone
VC Vehicle Commander
VTC Vehicle Technology Conference
VTI Vetronics Technology Integration
W Watt
WIN-T Warfighter Information Network-Tactical
WSMS Weapon System Mapping Service
XML Extensible Markup Language
XUV eXperimental unmanned vehicle
Zn Zinc
ZnO Zinc Oxide

TECHNOLOGY FOR THE SOLDIER

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CONTRIBUTING EDITORS

Cathi Brents, Alion/MA&D
Ginny Fite, GDRS
Pearl Gendason, ARL
Michael Jose, Honeywell
Patricia McDermott, Alion/MA&D
Simon Tsang, Telcordia
Susan Wright, BAE Systems

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